Arnold Schwarzenegger
Governor

DEPLOYMENT OF THE REVERSE ANNULUS SINGLE-ENDED RADIANT TUBE (RASERT)

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Deployment of the Reverse Annulus Single-Ended Radiant Tube (RASERT), is the final report for the Deployment of the Reverse Annulus Single Ended Radiant Tube (RASERT) project (Contract Number 500-06-015) conducted by the Gas Technology Institute. The information from this project contributes to PIER's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

This report describes the development and extended field trial of an advanced, highly efficient reverse-annulus, single-ended radiant tube (RASERT). A RASERT is a natural gas-fired heating element (burner) that is used to melt metals in furnaces without also introducing the associated combustion gases into the furnace. Only radiant heat is directed into the furnace while combustion gases are vented to the outside of the furnace chamber. A prototype was developed and tested under laboratory conditions, and 12 RASERTs based on the prototype design were deployed in a steel galvanizing line operated by California Steel Industries. Steel galvanization is a metallurgical process that is used to coat steel or iron with zinc. This is done to prevent galvanic corrosion (specifically rusting). The zinc reacts with oxygen in air to form a protective coating for the underlying steel. The process requires a controlled atmosphere with thermal heat without combustion gases. The current burner technology for this industrial process uses a single-ended radiant tube (SERT). This project compared the existing SERT design with the new RASERT design. Following the retrofit, a comparison of RASERT burner performance with the baseline performance of SERT burners in the retrofitted zone showed that the new RASERT burners produced a 25 percent improvement in thermal efficiency. Emissions of oxides of nitrogen (NOx), carbon monoxide (CO), and carbon dioxide (CO_2) were reduced by approximately 55 percent, 58 percent, and 25 percent, respectively. As a result of the retrofit in an estimated 2 billion BTU of natural gas per year will be conserved at the facility. California has an estimated 5,200 radiant tube assemblies currently in operation. Adoption of this technology state wide could prevent an estimated 187 tons of NOx and 48,250 tons of CO_2 from being emitted into the atmosphere.

Keywords: Radiant heating, radiant tube, galvanizing line, single-ended radiant tube (SERT), reverse-annulus single-ended radiant tube (RASERT), steel, heat treating

Executive Summary

Introduction

California's heat treating industry currently uses four technologies to provide process heating in atmosphere-controlled furnaces in the ferrous and non-ferrous metals industry: Gas-fired radiant U-tubes, straight-through tubes, gas-fired single-ended radiant tubes (SERTs), or electric resistance heating elements. A typical single ended radiant tube design is shown in Figure 1. California has an estimated 5,200 radiant tube assemblies currently in operation. Problems with these heating techniques include premature tube failure (leading to costly furnace downtime and production losses), average energy efficiencies of only about 50 percent when straight-through radiant tubes are used, and oxides of nitrogen (NOx) emissions of about 340 tons per year.

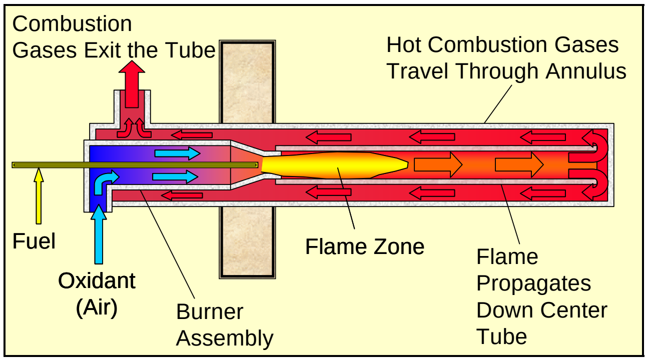


Figure 1. Conventional SERT Design

Source: Gas Technology Institute, 2008

The Gas Technology Institute (GTI) and North American Manufacturing Company (NAMCO) have developed a new technology called the reverse annulus single-ended radiant tube (RASERT), shown in Figure 2, which addresses these problems. The unique RASERT design is an improvement over other single-ended radiant tube designs, since combustion occurs in an annulus, or ring, around a central firing tube, which then conveys exhaust products resulting from combustion back to the burner end of the assembly. There, waste heat can be recovered and transferred to combustion air and fuel as they enter the burner. RASERT burner assemblies can have much higher thermal efficiencies than straight-through tubes and produce lower firing tube temperatures than other SERT systems, since combustion occurs outside the firing tube. RASERT components can, therefore, be manufactured from lower-cost materials. Thermal efficiency is the amount of useful heat transferred to the furnace divided by the total heat generated when the fuel gas is burned. The SERT system used before to the retrofit were approximately 50 percent thermally efficient (50 percent of the heat entered the furnace and 50 percent escaped in the exhaust gases or through the walls of the furnace). The new RASERT system was shown to be approximately 65 percent thermally efficient (65 percent of the heat entered the furnace and 35 percent escaped in the exhaust gases or through the walls of the furnace). Increasing the thermal efficiency enables the operator to process the same amount of finished steel while burning less natural gas.

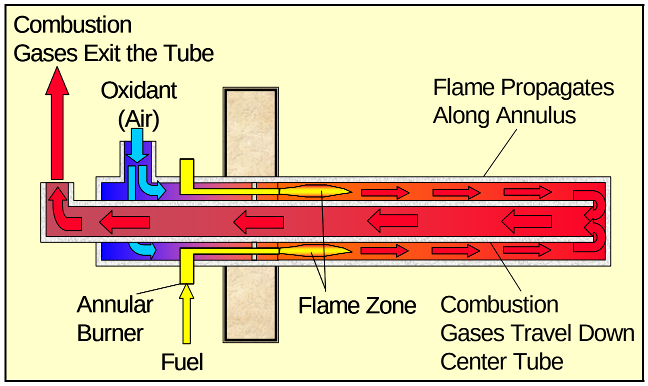


Figure 2. GTI RASERT Concept

Source: Gas Technology Institute, 2008

Purpose

This agreement will:

- Collaborate with the host site, California Steel Industries, Inc. (CSI), for technology deployment.
- Conduct repeated performance-verification analysis of a RASERT prototype fabricated by NAMCO.
- Build 12 commercial RASERTs by NAMCO for installation by CSI.
- Gather information of the installed RASERTs to confirm performance metrics (Tube temperature uniformity, average outer tube temperature, thermal efficiency and NOx emissions).
- Establish a technology transfer and commercialization plan.

Project Objectives

This agreement will demonstrate the following benefits of the RASERT technology relative to current cold air, straight-through radiant tube burners as:

- A fuel reduction of 38 percent based on an increase in available heat to 68 percent from the current estimated average of 42 percent.
- A reduction in NOx of approximately 50 percent.
- Carbon monoxide (CO) and carbon dioxide (CO_2) reductions of approximately 45 percent.

Project Outcomes

An improved RASERT design was developed in collaboration with North American Manufacturing Company and validated through laboratory testing at the Gas Technology Institute and independently at NAMCO. Twelve RASERT burners were installed in Zone 6 of the No. 1 Galvanizing Line at the Fontana, California facility of California Steel Industries. These burners replaced non-recuperated radiant tube burners and were investigated in detail after installation. The retrofit was shown to provide the following benefits:

- A fuel consumption reduction of 25 percent. The thermal efficiency of burners in the zone before the retrofit was approximately 50 percent. Under normal operating conditions following the retrofit, the RASERTs delivered approximately 65 percent thermal efficiency.
- NOx emissions were reduced by 55 percent.
- CO emissions were reduced by 58 percent.
- CO_2 emissions (carbon equivalent) were reduced by 25 percent.

Conclusions

The RASERT technology was shown to be effective and commercially viable and to provide benefits that will make adoption of the RASERT attractive in a wide variety of applications. Other radiant-tube burner research at the Gas Technology Institute combustion laboratory, funded by other sponsors, has shown that improvements beyond that demonstrated in this project have a high potential to be incorporated into a new and improved prototype for evaluation.

Benefits to California

As a result of the retrofit in Zone 6, an estimated 2 billion BTU of natural gas per year will be conserved at the Fontana facility, and the retrofit will reduce NOx emissions from Zone 6 by an estimated 492 pounds annually. The retrofit will reduce CO emissions by an estimated 243 pounds annually and CO_2 emissions by an estimated 232,000 pounds (116 tons) annually. More importantly, the RASERT technology has been shown to be a commercially viable alternative to traditional, non-recuperated burners and for recuperated burners and now has strong potential for wide acceptance in radiant heating applications to improve. RASERT technology has the potential to improve temperature uniformity, increase service life and thermal efficiency, and reduce NOx emissions.

1.0 Introduction

1.1. Background and Overview

California's heat treating industry currently uses four technologies to provide process heating in atmosphere controlled furnaces in the ferrous and non-ferrous metals industry: gas-fired radiant U-tubes, straight-through tubes, gas-fired single-ended radiant tubes (SERTs) or electric resistance heating elements. California has an estimated 5,200 radiant tube assemblies currently in operation. Problems with these heating techniques include premature tube failure (leading to costly furnace downtime and production losses), average energy efficiencies of only about 50 percent when straight-through radiant tubes are used, and oxides of nitrogen (NOx) emissions of about 340 tons per year including approximately 193,000 tons per year of CO_2 in terms of carbon equivalent.

The Gas Technology Institute (GTI) and North American Manufacturing Company, Ltd. (NAMCO) have developed a new technology called the Reverse Annulus Single Ended Radiant Tube (RASERT) which addresses these problems. The unique RASERT design is an improvement over other single-ended radiant tube designs, since combustion occurs in an annulus around a central firing tube, which then conveys exhaust products resulting from combustion back to the burner end of the assembly. There, waste heat can be recovered and transferred to combustion air and fuel as they enter the burner. RASERT burner assemblies can have much higher thermal efficiencies than straight-through tubes, and produce lower firing tube temperatures than other SERT systems, since combustion occurs outside the firing tube. RASERT components can, therefore, be manufactured from lower-cost materials.

1.2. Project Objectives

The objective of this Agreement is to demonstrate the following benefits of the RASERT technology relative to current cold air, straight-through radiant tube burners as:

- A fuel reduction of 38 percent based on an increase in available heat to 68 percent from the current estimated average of 42 percent.
- A reduction in NOx of approximately 50 percent.
- Carbon monoxide (CO) and carbon dioxide (CO_2) reductions of approximately 45 percent.

These objectives were to be achieved by development and laboratory validation of an improved RASERT design, and a field test, in the course of which twelve radiant tubes in a steel galvanizing line were to be retrofitted with RASERTs.

1.3. Report Organization

The sections of this report describe the following:

Section 1: Introduction

Section 2: Project Approach

Section 3: Project Outcomes

Section 4: Conclusions and Recommendations

2.0 Project Approach

Work on this project was broken down into five tasks, with subtasks identified where necessary. The full details of these tasks and subtasks were stated in the agreement developed when the project was initiated; summaries are provided below.

- TASK 1.0 ADMINISTRATION
    - Task 1.1 Attend Kick-off Meeting
        - The goal of this task is to establish the lines of communication and procedures for implementing this Agreement.
    - Task 1.2 CPR Meetings
        - The goal of this task is to determine if the project should continue to receive Energy Commission funding to complete this Agreement and if it should, are there any modifications that need to be made to the tasks, deliverables, schedule or budget.
    - Task 1.3 Final Meeting
        - The goal of this task is to close out this Agreement.
    - Task 1.4 Monthly Progress Reports
        - The goal of this task is to periodically verify that satisfactory and continued progress is made towards achieving the research objectives of this Agreement.
    - Task 1.5 Test Plans, Technical Reports and Interim Deliverables
        - The goal of this task is to set forth the general requirements for submitting test plans, technical reports and other interim deliverables, unless described differently in the Technical Tasks.
    - Task 1.6 Final Report
        - The goal of this task is to prepare a comprehensive written Final Report that describes the original purpose, approach, results and conclusions of the work done under this Agreement. The Commission Contract Manager will review and approve the Final Report. The Final Report must be completed on or before the termination date of the Agreement.
        - Task 1.6.1 Final Report Outline
            - The Contractor shall prepare a draft outline of the Final Report.
        - Task 1.6.2 Final Report

        - The Contractor shall prepare the draft Final Report for this Agreement in accordance with the approved outline.
  - Task 1.7 Identify and Obtain Matching Funds
    - The goal of this task is to ensure that the match funds planned for this Agreement are obtained for and applied to this Agreement during the term of this Agreement.
  - Task 1.8 Identify and Obtain Required Permits
    - The goal of this task is to obtain all permits required for work completed under this Agreement in advance of the date they are needed to keep the Agreement schedule on track.
  - Task 1.9 Electronic File Format
    - The goal of this task is to unify the formats of electronic data and documents provided to the Energy Commission as contract deliverables. Another goal is to establish the computer platforms, operating systems and software that will be required to review and approve all software deliverables.
- TASK 2.0 LAB TESTING (TECHNICAL TASK)
  - The goal of this task is to conduct repeated performance-verification analysis of a RASERT prototype fabricated by NAMCO under lab instrumented conditions. The combustion laboratory test site is located at GTI in Des Plaines, IL.
- TASK 3.0 FIELD PREP AND SUPPORT (TECHNICAL TASK)
  - The goal of this task is to prepare a field deployment evaluation plan including site measurement and control, and pre-establish technical bases for the demonstration with CSI, Inc.
- TASK 4.0 RASERT DEPLOYMENT, INFORMATION GATHERING AND REPORTING
  - The goal of this task is to collect pertinent information, and reduce and analyze the field data to establish the performance metrics of the RASERT systems as shown compared to previous base line data.
- TASK 5.0 TECHNOLOGY TRANSFER ACTIVITIES
  - The goal of this task is to develop a technology transfer plan that includes: knowledge gained, cumulative results (improvement in emissions over the life of the project and final fuel efficiency of the burner), exchange field information and lessons learned available to key decision-makers.

3.0 Project Outcomes

3.1. Timeline

December 2006:

Task 1:

Matching funds identified, letters obtained

December 12, 2006: Project kickoff meeting (conference call) w/ Energy Commission

December 13, 2006: Project kickoff meeting (conf call) w/ CSI and NAMCO

January 2007:

Task 1:

Permit application South Coast ACMD submitted by Michael Di Constanzo, senior environmental engineer, California Steel Industries

Task 2:

The heat treat furnace at the GTI Combustion Laboratory was prepared for testing. Verified readiness of GTI's laboratory test equipment for emissions and temperature measurement. T/Cs, et al were wrung out and checked for readiness.

February 2007:

Task 2:

CSI removed a previously installed RASERT, related to a prior project, for inspection. The previously installed RASERTS have been in operation since June 2006. It was determined that an internal component called the stabilizer ring will likely require a more heat resistant alloy and/or incorporate a change in design. This was reviewed with NAMCO and this change was reflected in a prototype that was fabricated for GTI lab testing and eventual retrofitted in regard to this project. After conferring with NAMCO, it was decided to postpone the immediate lab testing of the then prototype RASERT that was installed in GTI's lab furnace. NAMCO fabricated a revised prototype for receipt mid March that replicated what was currently installed at CSI. NAMCO modeling indicated that several further alterations to the internal design had the potential to promote greater temperature uniformity while minimizing effects on NOx emissions or thermal efficiency. Consequently, it was agreed that NAMCO would fabricate and provide the further-altered RASERT unit that operates with a primary-air fuel mixture at 25 percent FGR and the secondary air at 12 percent FGR to reduce peak temperature in the cross-over area. The GTI decision to incorporate several promising changes in the RASERT and test that prototype introduced about a two week delay in our plan. Since the test furnace had been prepared and the DAQ wrung out, testing commenced within two- days of receiving the insert and allowed make up of time during the remainder of testing.

Task 3:

CSI reported the following information regarding zone No. 6 which is the target zone for this retrofit: The majority of temperature set points range from 1250 °F to 1650 °F; the average temperature range is 1400 °F to 1450 °F

March 2007:

Task 1:

Martin Linck was added to the project; the permit application was approved; $5,200 was moved from 1.1 to 1.4 and approved; phone conference between CSI, GTI, and NAMCO was held to discuss the evolution of the RASERT Design

Task 2:

GTI performed a laboratory test of one version of the RASERT burner. The first RASERT version to be tested was returned to NAMCO for modification; and NAMCO returned the modified unit to GTI for a second test. Project work was accelerated; and additional staff assistance (Dr. Martin Linck) allowed GTI to regain its originally planned testing schedule.

Task 3:

NAMCO performed modeling and, together with GTI, selected two additional RASERT prototypes for testing. GTI, CSI, and NAMCO held a phone conference to update CSI about the current modeling and testing developments. Retrofit schedule was discussed, but not established at this time.

April 2007:

Task 1:

Deliverable date for Task 2 changed from 4/30/07 to 5/15/07, approved.

Task 2:

GTI performed the remaining two lab tests on the RASERT burner.

May 2007:

Task 1:

CSI signed and approved a field test agreement

Task 2:

GTI submitted the INTERIM LAB TEST SUMMARY REPORT (Deliverable)

Task 3:

The CPR meeting was rescheduled for June 12, 2007 from the planned May 15 date. A draft RASERT Field Test Plan was prepared. GTI hosted a telephone conference with CSI and NAMCO to discuss the timeline for RASERT deployment, and to inform CSI of the test results and burner design changes. GTI let a purchase order with NAMCO for 10 of the 12 RASERTs to be retrofitted. Expected ship date of 12 RASERTs to California Steel was August 10, 2007. NAMCO let a purchase order with their supplier for the internal radiant tubes (long lead time item).

June 2007:

Task 1:

The Critical Project Review (CPR) meeting was held on June 12, 2007. Reallocation of a portion of the funding between tasks and the deployment and testing schedule were discussed.

Task 3:

The Draft Field Test plan was approved as part of the field prep and support. GTI conveyed CSI's request to first retrofit Zone 7 with the new burners and then retrofit Zone 6 with rebuilt burners currently in Zone 7. CSI began pulling burners from Zone 7 to ship back to NAMCO for rebuild, according to schedule. A site visit was planned for on/about July 30, 2007 to discuss the field test procedure and verify that all necessary plans have been made for the field test in October.

July 2007:

Task 3:

A site visit (CSI) occurred on July 30 as the final step in field test planning. While other work continued that was related to Task 3, this work was carried out by project partners, and was not funded via project funds. Changes were made to the plan for the field test; RASERT burners scheduled to be installed in Zone 6 at CSI's facility would, instead, be installed in Zone 7 as replacements for RASERT prototypes installed previously. Zone 6 was to be equipped with rebuilt RASERTs, assembled using components of the prototypes removed from Zone 7. It was anticipated that the project should be completed by the date originally called for in the plan. Finite Element Analysis and Material Analysis were initiated by NAMCO (at their cost) of a RASERT removed from No. 7 zone of the galvanizing line at California Steel and returned to NAMCO for an evaluation. This RASERT along with nine others were retrofitted under a previous project in June 2006. The purpose of this evaluation was to discern whether there were any potential failure mechanisms evident after approximately 8,000 hours of relatively high temperature operation.

August 2007:

Task 1:

Draft No-cost time extensions were prepared, finalized. Revised and deployment dates were determined. California Steel Industries was notified of the delay and the potential new time frame, Mr. John Wray advised that the delay was to be coordinated with the furnace outage schedule. Magus Consulting Service was notified of the delay and the potential new time frame. Mr. Carl Bergstrom advised that the change can be accommodated.

Task 3:

RASERT prototype units currently installed in Zone 7 have been in operation for over one year. Issues with local overheating of the prototypes were noted. Steps were taken to address this issue prior to the field test (Zone 6) scheduled for this project. NAMCO undertook an extensive effort to redesign components of the RASERT in order to improve burner longevity. FLUENT modeling and finite element analysis were carried out, and a revised burner manufacturing and deployment schedule was developed.

September 2007:

Task 1:

No-cost time extensions submitted to Energy Commission and the co-sponsor UTD.

Task 3:

New burner design was under development. Extensive numerical modeling and prototype testing were underway at NAMCO; GTI provided development and design advice. Revised deployment schedule had been developed, but still depended on success of revisions made to burner design.

October 2007:

Task 3:

New burner design was completed. Prototype testing, using a welded prototype, proceeded at NAMCO. Castings of revised design were ordered, and manufactured.

Task 4:

A conference call between GTI, NAMCO and CSI was held to review the revised design; the onsite delivery of the RASERTs; and details of a thermocoupled radiant tube (outer and inner to be prepared by CSI. The existing Field Test Agreement between GTI and CSI needed amending to reflect the change in the period of performance. Revised deployment schedule was established, but still depended on delivery of castings and results of final prototype tests at NAMCO. On site delivery for No. 6 zone was set for April 29, 2008

November 2007:

Task 3:

Prototype testing, using a welded prototype, proceeded at NAMCO. Castings of revised design have been ordered, and were delivered to NAMCO for testing. Revised deployment schedule was developed, but still depended on delivery of production castings and results of final prototype tests at NAMCO. Preparations began at CSI in Fontana, CA, for an outage planned in December. Thermocouples were ordered and sent to CSI so that radiant tube temperature measurements could be provided for upcoming tests.

December 2007:

Task 3:

New burner design was completed. Prototype testing, using a welded prototype, proceeded at NAMCO. Castings of revised design were ordered, and manufactured. Revised deployment schedule was developed, and current progress indicated that schedule would be met. An FEA by a local subcontractor was initiated by NAMCO to round out the CFD analysis and physical testing that was carried out.

Task 4:

Thermocouples (27 T/Cs) were ordered and delivered to CSI for instrumentation of one RASERT burner and radiant tube during field trial. Six thermocouples sent to NAMCO for instrumentation of a firing tube, to be installed in an instrumented radiant tube that will contain a RASERT. A startup procedure and other relevant documentation were developed, based on results obtained during laboratory testing.

January 2008:

Task 3:

New results of numerical modeling and FEA analysis were reviewed in a conference call with NAMCO on 01/23/08. Generally, the results appeared promising; the particular components that overheated during previous tests appear to be operating at lower temperatures now. However, certain issues remained; the combustor can surrounding the flame stabilization region still showed some overheating. It was the considered judgment of the project team that this was not a vital issue; the components in question will not likely cause a failure of the burner if they oxidize or break down. However, further FEA analysis was to be pursued, in order to examine strategies which may allow this issue to be addressed. NAMCO advised that the scheduled on site delivery to CSI of the modified RASERTs would not be impacted.

February 2008:

Task 3:

Prototype testing and development continued. As of 02/27/08, the overall performance of the burner appeared to be satisfactory; lighting was no longer a problem. Under the most demanding conditions, however, i.e., during cold ignition of the burner, it was found to be difficult to detect the flame using an UV flame sensor. Work was in progress to correct this issue, and to proceed to further testing prior to deployment of the burner. RASERT deployment dates were pending due to these latest delays. Decisions were to be made in March as to final deployment dates.

March 2008:

Task 3:

A final prototype design was arrived at. This version had the required characteristics needed for the field trial at CSI, and a production and shipment schedule was developed. At present, RASERTs needed to begin the retrofit of Zone 6 at CSI were expected to be delivered June 20, 2008.

April, 2008:

Task 4:

The components needed for the retrofit of Zone 6 at CSI were now being manufactured at NAMCO. Conversations continued between project participants to coordinate preparations for the retrofit.

May 2008:

Task 4:

The components needed for the retrofit of Zone 6 at CSI were continuing to be manufactured at NAMCO. The on-site date for the RASERT burners was scheduled for June 13, 2008. Project status reviews (phone conferencing) continued between project participants to coordinate preparations for the retrofit.

June, 2008:

Task 4:

The components needed to convert the conventional cold-air radiant tube burners to RASERTs were shipped and received by CSI. The No.1 Galvanizing line was shut down for a planned outage on June 14th. The site visit by GTI occurred June 17th, while the line was down. Relevant dimensions of the Galvanizing line were obtained, and an appropriate location for data collection equipment was identified. Thermocouples attached to a radiant tube (tube No.69 South) and the associated firing tube were inspected. Issues with several of the thermocouples were identified, and plans were developed to make a minimum of six thermocouples available on the firing tube, and at least 18 thermocouples available on the radiant tube. Plans were made for GTI personnel to return to CSI July 7th through the 14th. Plans were developed for a separate site visit (June 29th and 30th) by NAMCO, in order to tune the RASERTs once they have been installed. After the site visit by GTI, CSI personnel proceeded with the installation of RASERT components in Zone No.6. Problems were encountered with the thermocouples installed on the firing tube of the No.69 South burner; (became detached). Per CSI consultation with GTI, it was determined that a different type of thermocouple, featuring flat tabs that could be readily welded to the radiant tube, would be preferable. Arrangements were made to ship 10 of these thermocouples to CSI, so that the re-instrumented firing tube could be installed in the No.69 South burner no later than June 26th. These new and revised thermocouple assemblies were delivered and welded onto the firing tube by CSI, and the galvanizing line was brought back up to production June 29th and 30th. As planned, (NAMCO) tuned the RASERT burners in Zone No. 6 once the line was back up to production. No issues or concerns were encountered.

July 2008:

Task 1:

An NCTE applied for, revising final dates for completion of Tasks 4 and 5 from 08/31/08 to 11/30/08.

Task 4:

Site visit by GTI personnel occurred July 17th-13th. The full field test was carried out, and data was taken. The performance of the RASERTs was verified. One RASERT in Zone 6 was found to have an unusually high exhaust temperature, and a conference took place involving CSI, GTI, and NAMCO. The decision was made to investigate this RASERT in greater depth, but this investigation would not take place within the context of the present project.

August, 2008:

Task 1:

Awaiting approval of No Cost Time Extension (NCTE) request by GTI.

Task 4:

Trip report documenting findings of field trial finished and submitted for internal review on August 7th. Final report on work related to all tasks being prepared.

3.2. Task 1.0

As described in Section 4.1, activities related to Task 1 were ongoing throughout the project. The subtasks were completed when necessary, and when the opportunity to do so arose.

3.3. Task 2.0

The goal of this task was to conduct repeated performance-verification analysis of a Reverse Annulus Single-Ended Radiant Tube (RASERT) prototype fabricated by the North American Manufacturing Co. (NAMCO) under lab instrumented conditions. The combustion laboratory test site is located at GTI in Des Plaines, IL.

The first RASERT design (Variant I) was deployed in 2006 at the host site California Steel Industries (CSI) in Fontana, California, under a separate GTI contract. NAMCO has continued modeling and modifying the prototype to improve the following performance metrics:

BASIC PERFORMANCE METRICS
Tube Temperature Uniformity
Average Outer Tube Temp
Thermal Efficiency (Available Heat)
NO_x Emissions (@ 3 percent O_2)

GTI tested the CSI prototype to verify that performance matched the model predictions. Periodic telephone conferences were held between NAMCO and GTI to discuss modeling results and to change future models. After a satisfactory change in the model performance, several designs were selected for testing. GTI returned its burner body to NAMCO for a retrofit, and received a modified pseudo-tube assembly plus additional components for further retrofits.

Design changes were made to the stabilizer and the pseudo-tube; these burner parts can be changed without a major modification to the manufacturing process, but play a major role in the location of the flame root and in the flame mixing. The three designs that were tested are described below.

3.3.1. Approach

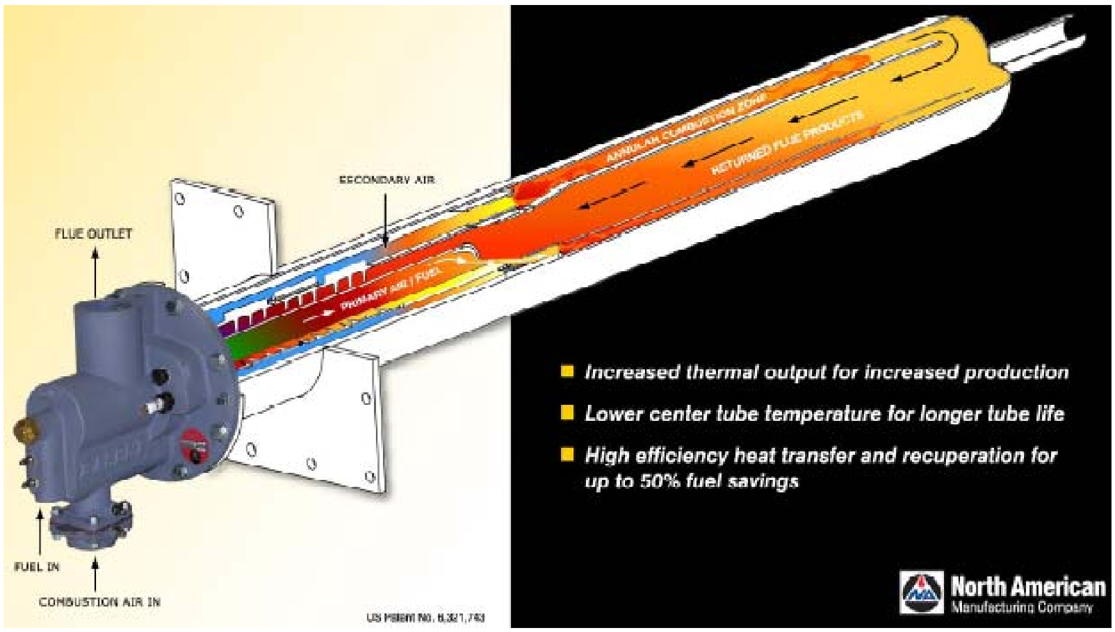


Figure 3. RASERT Product Literature from the Product Licensee (NAMCO)

Source: North American Manufacturing Company, 2008

The RASERT design effectively provides radiant heat for process applications, while reducing nitrogen oxide emissions, and improving the longevity of burner components. Every RASERT design features a body casting, recuperator section, pseudotube, and firing tube. These components are inserted into a radiant tube, which radiates heat to the process while preventing combustion products from coming into direct contact with product or other components in the furnace interior.

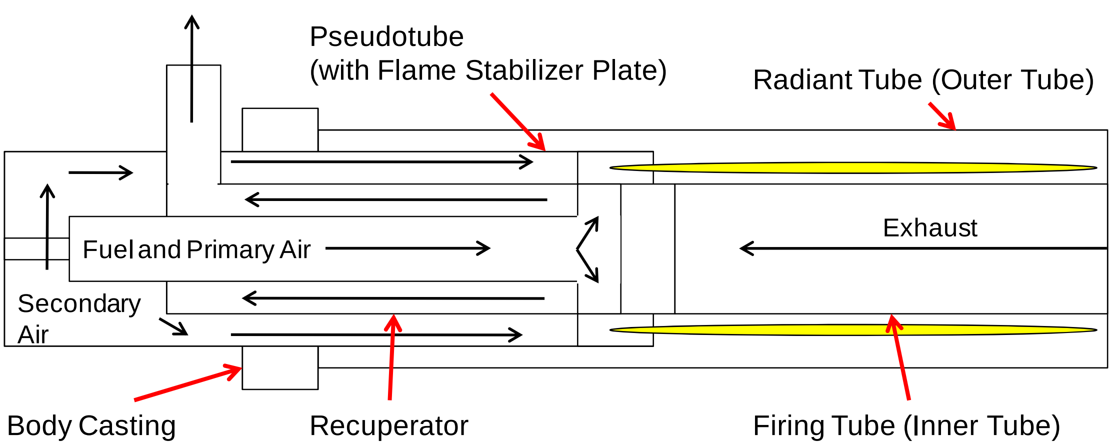


Figure 4. Cross-sectional view of assembled RASERT components

Source: Gas Technology Institute, 2008

The RASERT is up to 50 percent more fuel efficient than unrecuperated straight-through burners, since hot combustion products are recirculated back through the burner, and are used to preheat the incoming gases prior to combustion. In a straight-through burner, the combustion products are simply vented through an exhaust at the far end of the radiant tube, and the heat contained in these exhaust gases is wasted. Three new prototype variants were tested, featuring changes to the pseudotube (which stabilizes combustion), the recuperator (which preheats incoming combustion air to increase efficiency) and the firing tube (which channels combusting gases down the interior of the radiant tube).

3.3.2. Activities Performed

The prototype variants were tested in a heat-treating furnace equipped with a wide variety of instrumentation and data acquisition equipment. The furnace temperature for the relevant tests was 1650 °F, in order to match conditions in the steel galvanizing line at CSI. The burner was tested in the fully-instrumented heat treating furnace, in order to obtain detailed information about pollutant concentrations in the exhaust and temperature profiles along the firing and radiant tubes. The same furnace temperature was maintained for different RASERT firing rates by using two additional burners for auxiliary heating as needed.

The first variant (Variant I) of the RASERT design has already been deployed to a host site at California Steel Industries in Fontana, California. Ten of these prototype burners were inserted into pre-existing radiant tubes on zone No. 7 of California Steel's No. 1 horizontal continuous galvanizing line. The RASERTs were installed June 20th-22nd, 2006, as part of a previous project designed to demonstrate the potential of the RASERT technology. The pre-existing configuration was straight-through radiant tubes which had to be modified to convert them to single-ended radiant tubes.

A computer model of Variant I was created and studied for the current project, in order to identify strategies for improvement in the RASERT design. Per operating information provided by CSI including and photographs of the internals from several RASERTs that had been removed for inspection, additional computer models were generated with design changes that were iteratively refined and reviewed by NAMCO and GTI.

3.3.3. Variant I Laboratory Test
Scalloped Stabilizer Plate in Full-Length Pseudotube (Tested 03/30/07)

RASERT Variant I was tested in GTI's full-scale heat-treat test furnace on 03/30/07. Exhaust pollutant concentrations, available heat, and temperature profiles along the firing and radiant tubes were measured. These data provided a baseline for the remaining tests and also verified predictions made by the NAMCO computer models. Figure 11 and Figure 12 in the Photographs section below illustrate the aspects of the burner design that changed between design iterations. A side view of the "pseudotube" is best shown in Figure 14.

Field reports indicated that temperatures in the can were higher than was acceptable; parts of the Variant I stabilizer can design caused combustion within the can, and some deformation was observed in the RASERT installation at CSI. Figure 13 shows this deformation. Both the Variant I computer model predictions and the tube temperature profiles recorded during the Variant I laboratory tests indicated some uncombusted fuel and air were mixing and burning at the end of the radiant tube; this may be undesirable. Modifications were made to Variant II in order to address these issues.

3.3.4. Variant II Laboratory Test Shortened Pseudotube Plus Tabs (Tested 04/27/07)

Variant II was designed after several months of modeling and discussion—the pseudotube was shortened by cutting 1-1/4" from the end of the stabilizer can. The stabilizer can is the last part welded on to the end of the pseudotube. The stabilizer plate and holes on the stabilizer can were also modified with the intent to lengthen the flame. Some aspects of the exhaust gas recirculation were changed to maintain stability with the new stabilizer geometry.

To ensure no uncombusted fuel and air reach the end of the radiant tube, tabs (shown in Figure 16) were placed on the firing tube to turbulize the flow and promote combustion of the remaining fuel and air. The decision to incorporate multiple changes into a single test was made in order to achieve project objectives within the allotted budget, while also allowing a third test, which could be used to address any further issues.

3.3.5. Variant III Laboratory Test Shortened Pseudotube With Tabs Removed (Tested 05/07/07)

Variant III featured the same pseudotube geometry as Variant II, but the tabs were removed from the firing tube. This design change was made because, during testing of Variant II, the tabs successfully ensured complete combustion before flow reversal, but emissions data obtained from Variant II were worse than had been the case with Variant I. The goal of the final laboratory test was to identify precisely which performance changes were a consequence of the new pseudotube geometry, and which were a consequence of the addition of tabs on the firing tube.

3.3.6. Results

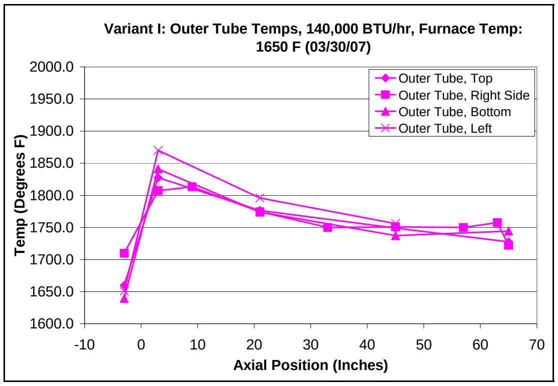
Tube temperature distribution and emissions data were recorded as a function of firing rate. For all of the tests, the fuel-to-air ratio was set to maintain 3 percent O_2 in the exhaust; an industry standard. Available heat, a measure of efficiency, was calculated from the exhaust temperature, the percent CO_2 in the exhaust, and the most recent analysis of GTI's natural gas composition. Each test lasted at least eight hours, and care was taken to ensure that the furnace temperature and combustion characteristics of the RASERT were stable when each data set was recorded. On the radiant tube, thermocouples were mounted along the top, bottom, left and right sides. On the firing tube, one thermocouple was mounted near the "crossover" (the point in the burner where combustion begins) and six further thermocouples were mounted, in pairs, along the left and right sides of the tube.

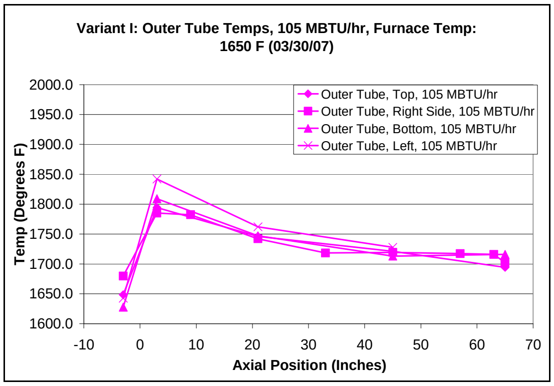
Variant I Laboratory Test: Scalloped Stabilizer Plate in Full-Length Pseudotube

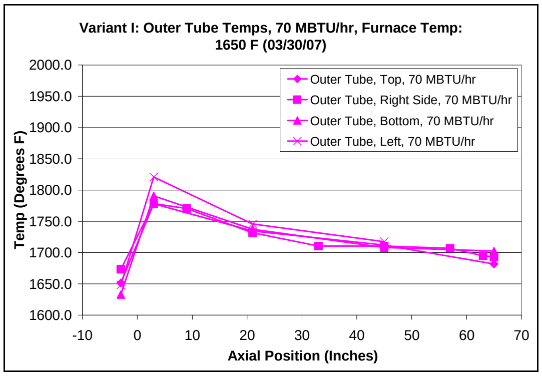
Table 1. Emissions and Exhaust Temperature Data for RASERT Variant I

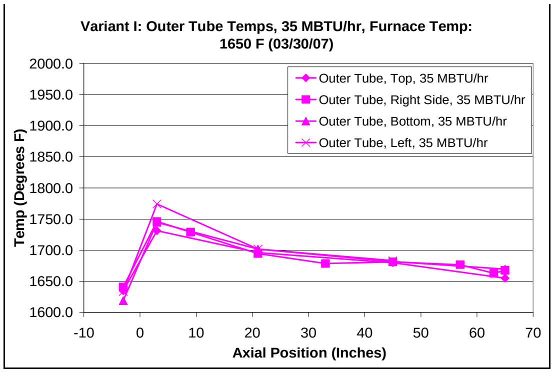
Source: Gas Technology Institute, 2008

Variant I, 1650 °F	RASERT Exhaust	Emissions						Available Heat
		NOx	CO	CO_2	O_2	NOx @ 3 percent O_2	CO @ 3 percent O_2	
Units	°F	ppmv	ppmv	percent	percent	ppmv	ppmv	percent
Firing rate 140 MBTU/hr	1244	50.0	15	--	3.01	50.0	15.0	61.2 percent
Firing rate 105 MBTU/hr	1111	43.5	19	11.0	3.01	43.5	19.0	64.8 percent
Firing rate 70 MBTU/hr	995	36.4	18	11.0	2.97	36.3	18.0	69.8 percent
Firing rate 35 MBTU/hr	809	27.4	50	11.0	3.01	27.4	50.0	72.5 percent









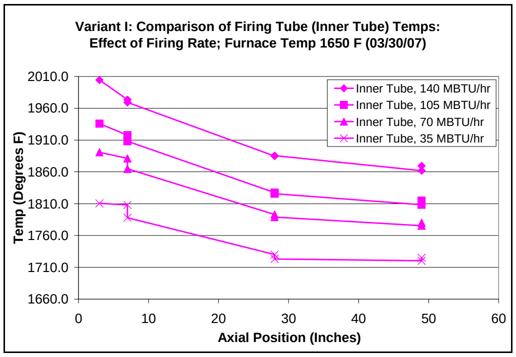


Figure 5. Temperature profiles obtained during testing of Variant I

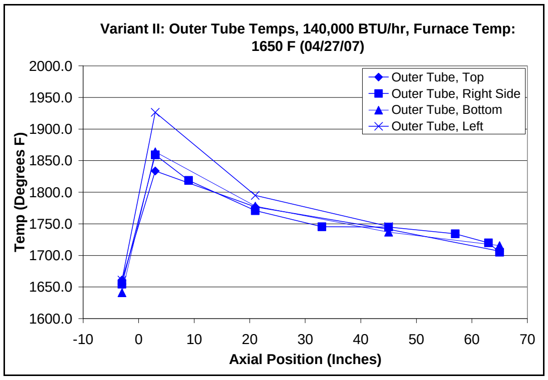
Source: Gas Technology Institute, 2008

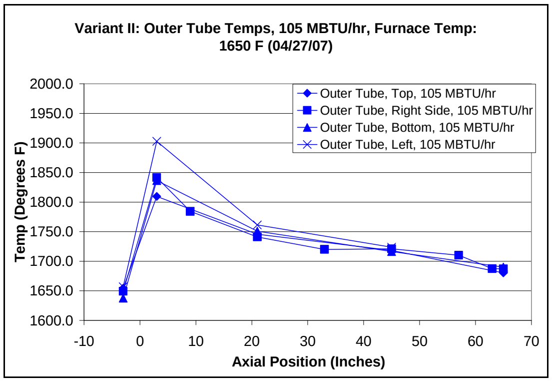
Variant II Laboratory Test: Shortened Pseudotube Plus Tabs

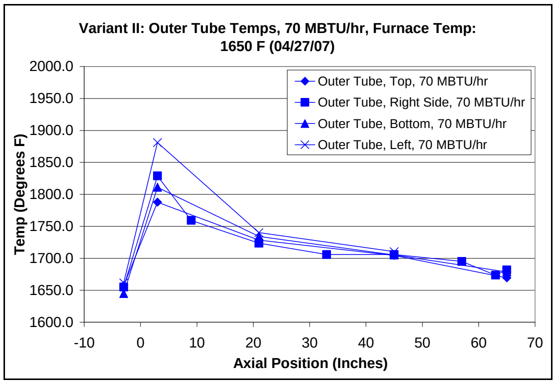
Table 2. Emissions and Exhaust Temperature Data for RASERT Variant II

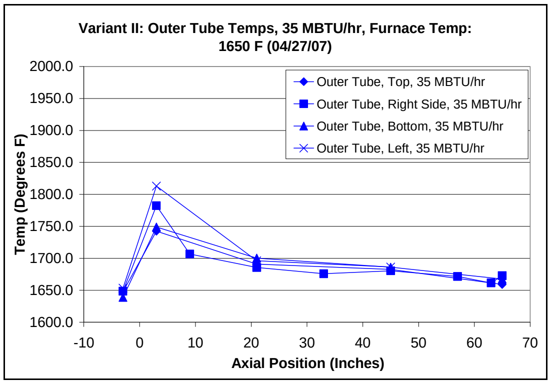
Source: Gas Technology Institute, 2008

Variant II, 1650 °F	RASERT Exhaust	Emissions						Available Heat
		NOx	CO	CO_2	O_2	NOx @ 3 percent O_2	CO @ 3 percent O_2	
Units	°F	ppmv	ppmv	percent	percent	ppmv	ppmv	percent
Firing rate 140 MBTU/hr	1120	58.6	23	11.0	3.02	58.7	23.0	66.2 percent
Firing rate 105 MBTU/hr	1027	51.1	24	11.0	3.00	51.1	24.0	68.5 percent
Firing rate 70 MBTU/hr	923	46.1	27	11.0	2.98	46.0	27.0	71.0 percent
Firing rate 35 MBTU/hr	682	28.1	28	10.9	3.01	28.1	28.0	76.6 percent









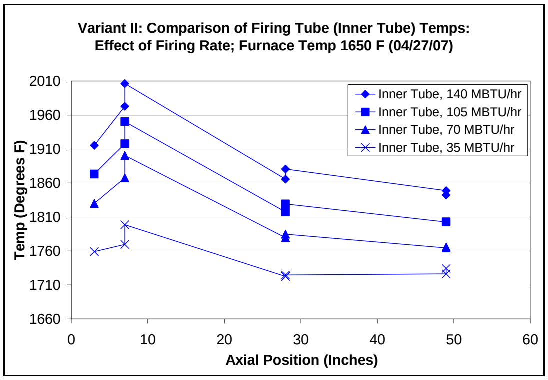


Figure 6. Temperature profiles obtained during testing of Variant II

Source: Gas Technology Institute, 2008

Variant III Laboratory Test: Shortened Pseudotube with Tabs Removed

Table 3. Emissions and Exhaust Temperature Data for RASERT Variant III

Source: Gas Technology Institute, 2008

	RASERT Exhaust	Emissions						Available Heat
Variant III, 1650°F		NOx	CO	CO_2	O_2	NOx @ 3 percent O_2	CO @ 3 percent O_2	
Units	°F	ppmv	ppmv	percent	percent	ppmv	ppmv	percent
Firing rate 140 MBTU/hr	1030	48.9	16	11.1	3.01	48.9	16.0	68.6 percent
Firing rate 105 MBTU/hr	928	43.4	27	11.1	3.00	43.4	27.0	71.0 percent
Firing rate 70 MBTU/hr	834	38.2	22	11.0	3.00	38.2	22.0	73.1 percent
Firing rate 35 MBTU/hr	720	34.5	30	10.8	3.08	34.7	30.1	75.6 percent

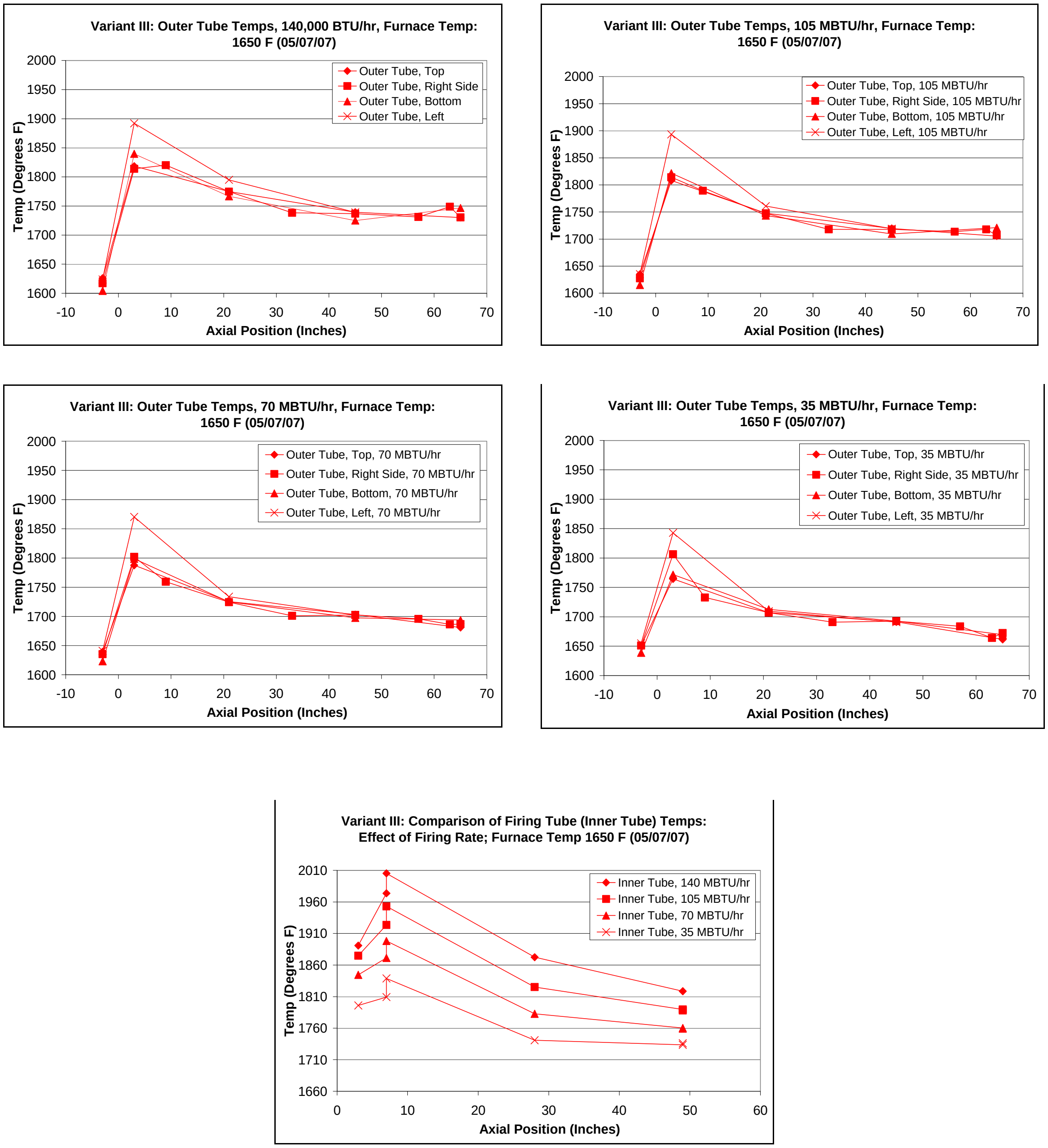


Figure 7. Temperature profiles obtained during testing of Variant III

Source: Gas Technology Institute, 2008

Analysis

Figure 8 below shows the radiant tube temperature distributions and the firing tube temperature distributions for conditions where each RASERT variant was being fired at 140,000 Btu/hr. These temperatures, and the emissions data summarized in Figure 9, redact the test results for comparison between the different RASERT variants. The axial position given in each plot is based on an origin located at the burner-end of the firing tube. Combustion therefore begins downstream of this origin, at an axial position between 0 and 10 inches.

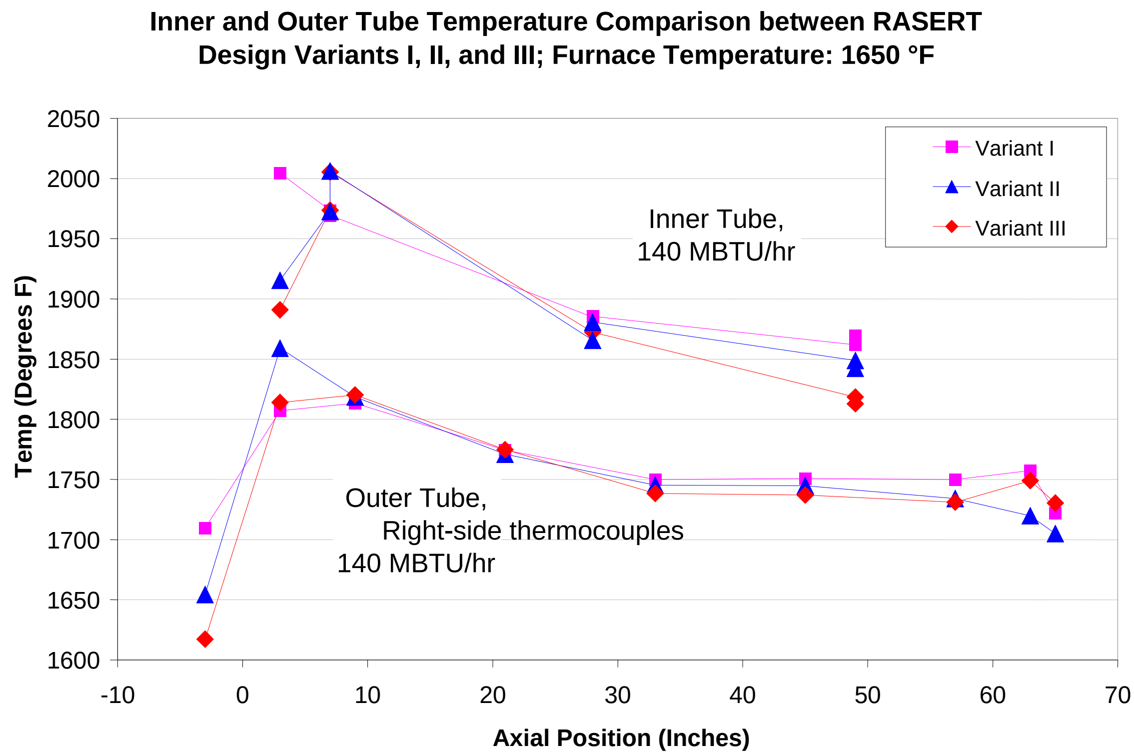
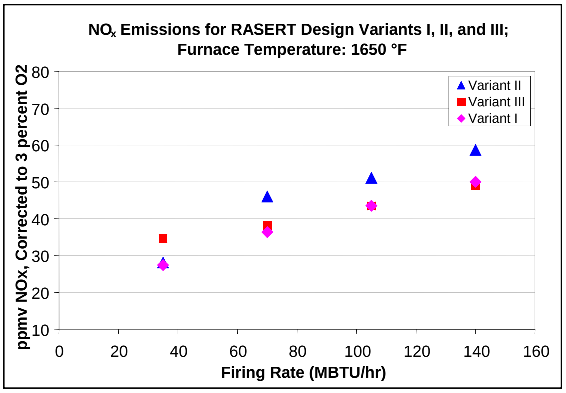


Figure 8. Inner and Outer Tube Temperature Comparison of RASERT Design Variants I, II, and III

Source: Gas Technology Institute, 2008



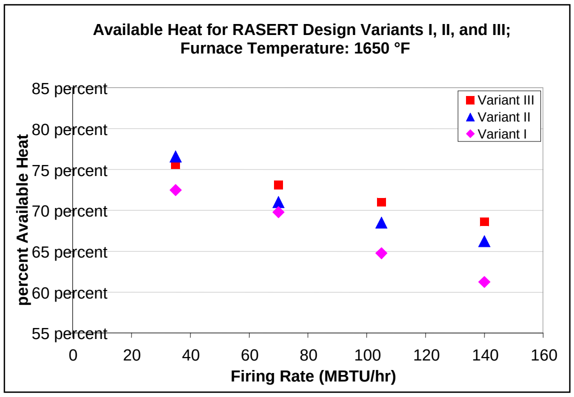


Figure 9. Available Heat and NOx Comparisons between RASERT Design Variants I, II, and III

Source: Gas Technology Institute, 2008

3.3.7. Discussion of RASERT Laboratory Tests

The new, shortened pseudotube in Variant II and Variant III is not exposed to the same peak temperature as was the design in Variant I. This can be seen in Figure 8, where the peak firing tube temperature is shifted from 3 inches downstream from the crossover to 7 inches downstream in the revised design. Because both Variant II and Variant III exhibit this temperature performance, it can be concluded that the new pseudotube design is responsible for the temperature reduction. This improved design appears to resolve issues encountered during the Zone 7 field test at CSI, and will be adopted soon on future commercial applications of this burner.

At the 140,000 Btu/hr firing rate, the only radiant tube temperature that is monotonically decreasing with increasing axial position is that associated with Variant II. Variant II was the only variant equipped with tabs on the firing tube. The monotonically decreasing temperature associated with this variant indicates that all fuel is combusted before the gases turn around, at the end of the radiant tube, and enter the firing tube. The tabs were therefore found to effectively eliminate unburned fuel in the annular space between the firing tube and radiant tube. However, Variant II displayed higher peak radiant tube temperatures than the other Variants (see Figure 8). Variant II also produced higher NOx concentrations in the exhaust (see Figure 9), and lower available heat than Variant III.

Variant III used the shortened, modified pseudotube, and had no tabs mounted on the firing tube. This variant produced higher available heat than either of the other variants, and emitted less NOx. Since there were no tabs present, some combustion near the far end of the tube was observed. However, the peak temperatures of the radiant and firing tubes were comparable with those of Variant I. It appears that Variant III therefore incorporates the most desirable performance characteristics. Further, it appears that the mixing effect produced by the tabs is not necessarily desirable. Delaying combustion of fuel in the outer annulus appears to reduce NOx formation, and does not appear to adversely impact thermal efficiency. Further, the presence of tabs on the firing tube appears to increase combustion temperatures upstream, where combustion is initiated, and creating greater thermal stress on the radiant tube.

Recommendations

It was recommended that design features incorporated into Variant III be used as the new burner to be deployed at CSI. Shorter pseudotubes will resolve local heating problems, but tabs need not be welded to the firing tubes of RASERT systems in the field at this point. While some additional mixing in the annulus may be desirable, further investigation by NAMCO will be necessary to design the exact type of modification to be made.

Issues Encountered

No significant issues were encountered while performing Task 2.0. The laboratory tests were delayed, relative to the original project schedule, because initially there was insufficient improvement in model performance to justify testing. Once the shortened pseudotube idea showed promise, both GTI and NAMCO worked to regain the lost time through rapid exchange of parts and information.

Implications

The test program was successful; iteration between computer models and laboratory tests combined to improve the RASERT's performance. Most important, the peak temperatures seen in the burner were moved away from the stabilizer can. A means has been identified by which complete combustion of fuel can be achieved before the combustible mixture reaches the end of the firing tube, and, ultimately, a strategy may be developed which will allow this effect to be achieved without negatively impacting other performance characteristics. The improved RASERT prototypes were expected to be deployed at CSI during the summer months; an eight week lead time between placement of an order of this size and delivery of the burners was identified. This overall schedule fell within the constraints of the original schedule.

3.3.8. Photographs

Variant I Laboratory Test: Scalloped Stabilizer Plate in Full-Length Pseudotube

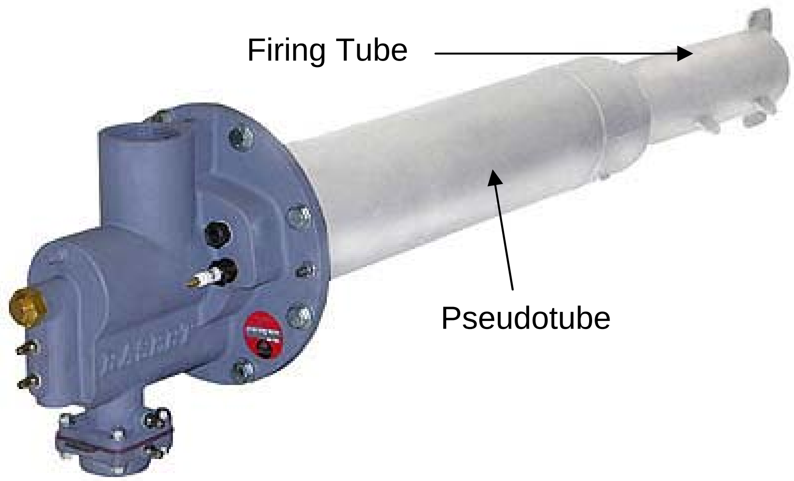


Figure 10. RASERT Variant I with pseudotube and firing tube identified

Source: North American Manufacturing Company, 2008

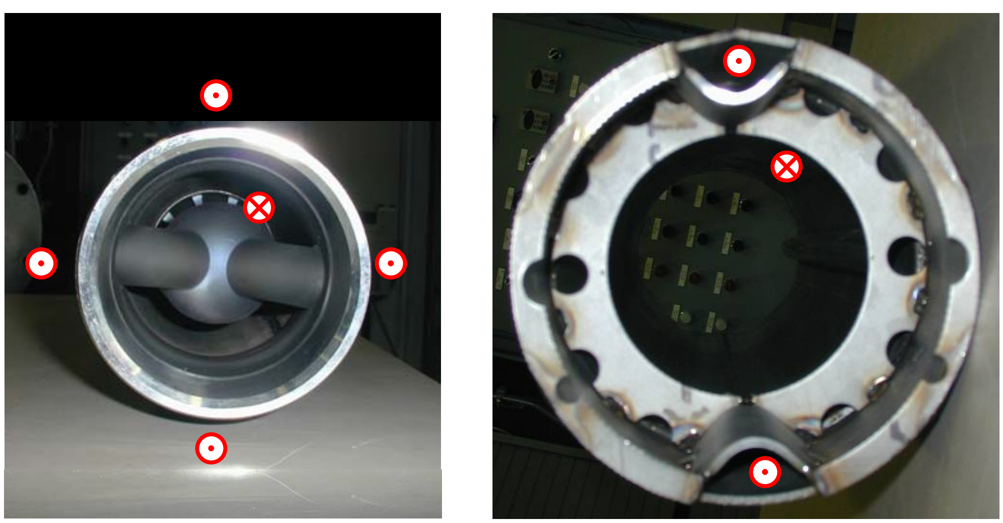


Figure 11. RASERT Variant I: Crossover casting in the heat exchanger weldment (left) and scalloped stabilizer plate and stabilizer ring (right)

Source: Gas Technology Institute, 2008

The photograph on the right in Figure 11 shows the view looking upstream into the pseudotube: at the top and the bottom of the tube are channels for the secondary air to flow into the annulus, and the round holes on the left and right are for the igniter and the flame monitor. The heat exchanger weldment (on the left) inserts into the center of the pseudotube (on the right.) Both of these components together would be installed into a larger radiant tube. Flow directions are illustrated by the circle symbols: the arrow head identifies regions where flow is out of the page, and the arrow tail identifies regions where the flow is into the page.

The horizontal parts on the left photograph in Figure 11 are the exits from the crossover casting. A mixture of fuel and air exits the crossover casting just downstream of the stabilizer plate (with the scallops, on the right photograph in Figure 11). The mixture is ignited, and retained to some extent by the stabilizer ring. Comparing Figure 12 with Figure 13 it is clear that the stabilizer can sustained some deformation during its operation (Zone No.7 – previous project). The Variant II design therefore focused on modifying the stabilizer can.

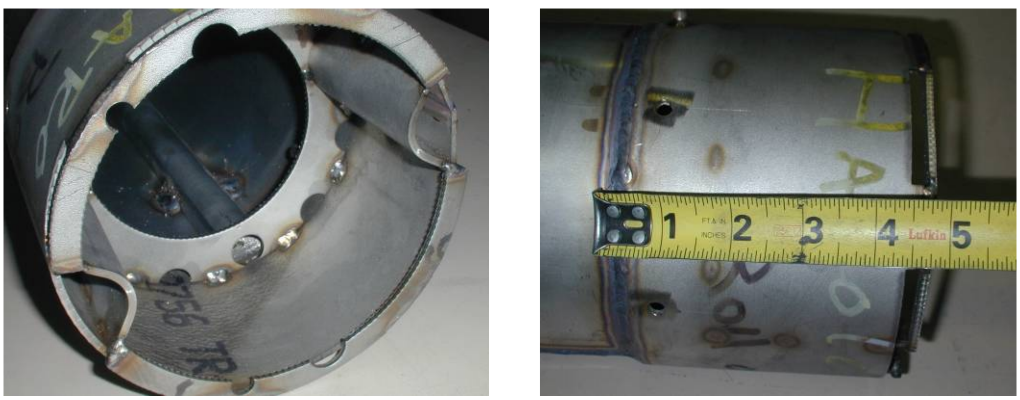


Figure 12. RASERT Variant I: Alternative views showing stabilizer can with ring

Source: Gas Technology Institute, 2008

Figure 13. RASERT Variant I: Burner No. 4 from the CSI Installation. Photograph from 1/30/2007, after seven months of service, mechanical damage was due to removal from bowed radiant tube

Source: California Steel Industries, 2008

Variant II Laboratory Test: Shortened Pseudotube Plus Tabs

Figure 14. RASERT Variant II: Shortened Pseudotube: Stabilizer ring had been cut from the can to expose the end of the heat exchanger weldment

Source: Gas Technology Institute, 2008

The design approach chosen to eliminate the problems shown in Figure 13 was straightforward; nevertheless the modeling performed to reach this point was extensive. About 1-1/4 inches of the stabilizer can at the end of the pseudo-tube were cut. In addition, the secondary air channels were increased in size, and the scallops on the stabilizer ring were removed. Certain flue gas recirculation patterns inside of the burner were also caused to be modified (not visible). Tabs were added to the firing tube as simple bluff bodies that would turbulize the flow; this enabled combustion to complete before the flow reversed at the end of the radiant tube. Because complete combustion was observed with the tabs, a second mixing option was not tried. Instead, Variant III was investigated, with the tabs removed to isolate impact of the tabs from the impact of the new stabilizer can design.

Figure 15. RASERT Variant II with shortened stabilizer can and modified secondary air channels

Source: Gas Technology Institute, 2008

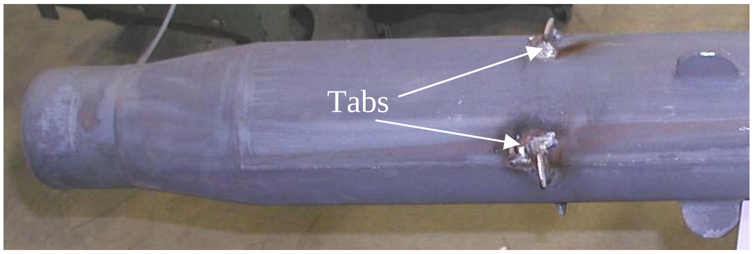


Figure 16. RASERT Variant II: Firing tube with tabs

Source: Gas Technology Institute, 2008

Variant III Laboratory Test: Shortened Pseudotube without Tabs

Figure 17. RASERT Variant III: Firing tube without tabs; pseudotube is unchanged

Source: Gas Technology Institute, 2008

3.4. Task 3.0

In February 2007, CSI reported the following information regarding zone No. 6 which was the target zone for this retrofit: The majority of temperature set points range from 1250 °F to 1650 °F; the average temperature range is 1400 °F to 1450 °F. In March 2007, NAMCO performed modeling and, together with GTI, selected two additional RASERT prototypes for testing. GTI, CSI, and NAMCO held a phone conference to update CSI about the current modeling and testing developments. The retrofit schedule was discussed, but not set at this time. In May 2007, the Critical Progress Review (CPR) meeting was rescheduled for June 12, 2007, as opposed to the original May 15 date. A draft RASERT Field Test Plan was prepared. GTI hosted a telephone conference with CSI and NAMCO to discuss the timeline for RASERT deployment, and to inform CSI of the test results and burner design changes. GTI let a purchase order with NAMCO for 10 of the 12 RASERTs to be retrofitted. At this point, the expected ship date of 12 RASERTs to California Steel was August 10, 2007. NAMCO let a purchase order with their supplier for the internal radiant tubes (long lead time item). However, the burner longevity issues discussed in section 4.3, above, necessitated an extensive re-design of the RASERT prior to the field test, and this delivery was ultimately delayed until June, 2008. In June 2007, the Draft Field Test plan was approved as part of the field prep and support task. At this point, GTI conveyed a request by CSI to first retrofit Zone 7 with the new burners and then retrofit Zone 6 with rebuilt burners currently in Zone 7. CSI began pulling burners from Zone 7 to ship back to NAMCO for rebuild. A site visit was planned for on/about July 30, 2007 to discuss the field test procedure and verify that all necessary plans have been made for the field test, which was still planned for October, 2007. A site visit (CSI) occurred on July 30 as the final step in field test planning. Changes were made to the plan for the field test; RASERTs scheduled to be installed in Zone 6 at CSI's facility would, instead, be installed in Zone 7 as replacements for RASERT prototypes installed previously. Zone 6 would then be equipped with rebuilt RASERT burners, assembled using components of the prototypes removed from Zone 7, after a revised design could be developed. It was anticipated that the project should be completed by the date originally called for in the plan, but the re-design of the RASERT took longer than anticipated. Finite Element Analysis and Material Analysis were initiated by NAMCO of a RASERT burner removed from No. 7 zone of the galvanizing line at California Steel and returned to NAMCO for an evaluation. The purpose of this evaluation was to discern what potential failure mechanisms had become evident after approximately 8,000 hours of relatively high temperature operation.

In August 2007, steps were under way to address issues discovered with the RASERT design prior to the field test scheduled for this project. NAMCO undertook an extensive effort to redesign components of the RASERT in order to improve burner longevity. FLUENT modeling and finite element analysis were being carried out, and a revised burner manufacturing and deployment schedule was under development.

By October 2007, a new burner design had been largely completed. Prototype testing, using a welded prototype, proceeded at NAMCO. Castings of parts needed for the revised design were ordered, and further prototypes were being manufactured.

In November 2007, prototype testing, using the welded prototype, proceeded at NAMCO. Castings of parts for the revised design had been ordered, and were delivered to NAMCO for testing. The revised deployment schedule had been developed, but still depended on delivery of production castings and results of final prototype tests at NAMCO. Preparations began at CSI in Fontana, CA, for an outage planned in December. Thermocouples were ordered and sent to CSI so that a radiant tube in Zone 6 could be equipped to provide temperature measurements for the field trial.

In December, 2007, the new burner design was completed. A Finite Element Analysis by a subcontractor was initiated by NAMCO to round out the CFD analysis and physical testing that was carried out.

New results of numerical modeling and FEA analysis were reviewed in a conference call with NAMCO on January 23rd, 2008. Generally, the results looked quite promising; the particular components that overheated during previous tests appeared to be operating at lower temperatures. However, the combustor can surrounding the flame stabilization region still showed some overheating. It was the best judgment of the project team that this was not a vital issue; the components in question would not likely cause a failure of the burner if they oxidized or broke down. However, further FEA analysis was pursued, in order to examine strategies which might allow this issue to be addressed. NAMCO advised that the scheduled on site delivery to CSI of the modified RASERTs would not be impacted. At this point, the required components were expected to reach CSI in the early summer.

In February 2008, prototype testing and development continued. As of February 27th, 2008, the overall performance of the burner appeared to be satisfactory; lighting was no longer a problem. Under the most demanding conditions, however, i.e., during cold ignition of the burner, it was found to be difficult to detect the flame using an UV flame sensor. Work was in progress to correct this issue, and to proceed to further testing prior to deployment of the burner. Burner deployment dates were pending due to these latest delays. Decisions would be made in March as to final deployment dates.

In March 2008, a final prototype design was arrived at. This version had the required characteristics needed for the field trial at CSI. The burners needed to begin the retrofit of Zone 6 at CSI would be delivered by June 20, 2008. The burners were then installed during an outage, and the line was brought back up to production, with RASERTs installed in Zone 6, on June 30th.

3.5. Task 4.0

3.5.1. Baseline Data

A trip to California Steel Industries (Fontana, CA) took place from January 31, 2006 through February 2, 2006. The purpose of this visit was to conduct Baseline Testing for the UTD RASERT development and demonstration project (GTI Project No. 20233). The information collected during these baseline tests was later used for comparison against the performance of the RASERT technology.

The target furnace is CSI's No. 1 Galvanizing Line, with the baseline test burner located at Burner No. 70 on the North Side (non-drive side). The baseline burner was a customized North American "Evenglow" model 4725-2-E spark ignited, cold air burner. It utilized a 6 5/8" ID, 7" OD, 119 ¾" long straight-through radiant tube. This burner/tube was situated above the strip, the last burner on the header of Zone 6 (of the seven zone reducing section of the furnace). This burner was selected due to a required tube change at this location. The burners on this furnace are all modulating via a pressure balance ratio regulator according to a PID controller.

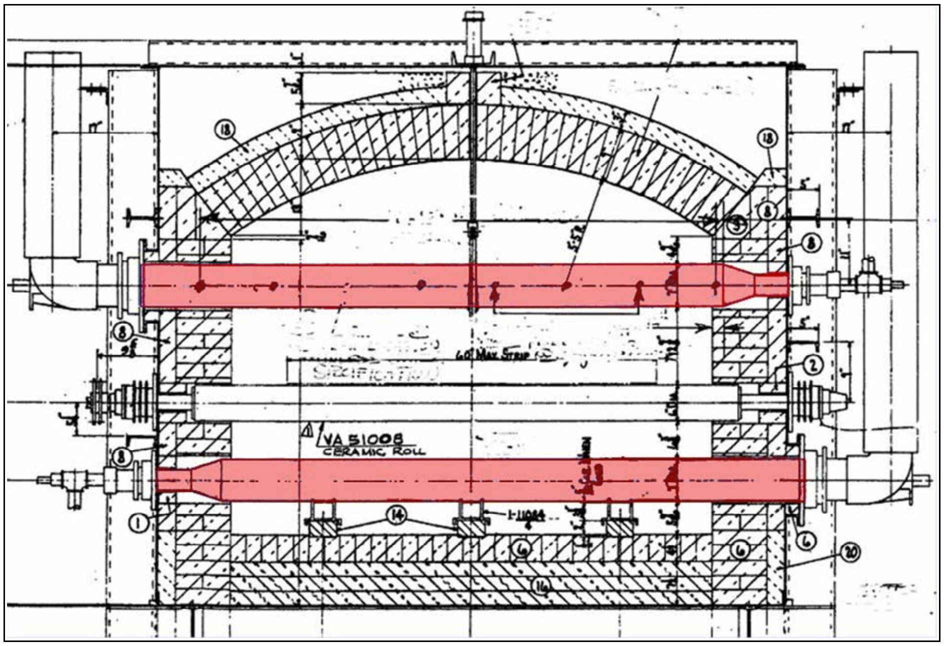


Figure 18. Cross Section of CSI Continuous Annealing Furnace

Source: California Steel Industries, 2008

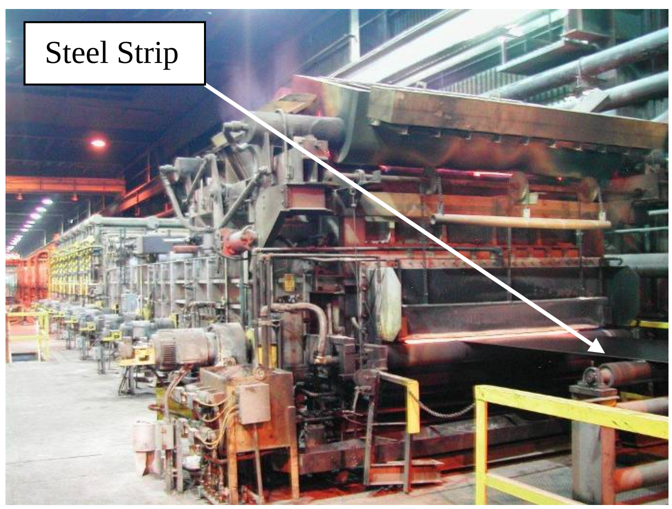


Figure 19. Strip entrance to No. 1 Galvanizing Line in the direct fired section

Source: Gas Technology Institute, 2008

Figure 20. Zone 6, South Side view, showing north side burner exhausts (above) the strip and south side burners (below) the strip

Source: Gas Technology Institute, 2008

Figure 21. No. 1 Galvanizing Line, Reducing Section, Zone 6, North Side, Burner No. 70 (Baseline Test Burner) Customized North American "Evenglow" model 4725-2-E spark ignited, cold air burner

Source: Gas Technology Institute, 2008

At 25 percent output (0.065 MMbtu/hr firing rate during a 1600 °F zone setpoint), the following combustion performance metrics were recorded:

- O_2 in Exhaust: 3.9 percent
- CO (@ 3 percent O_2): 1.9 ppmv
- NOx (@ 3 percent O_2): 95.1 ppmv

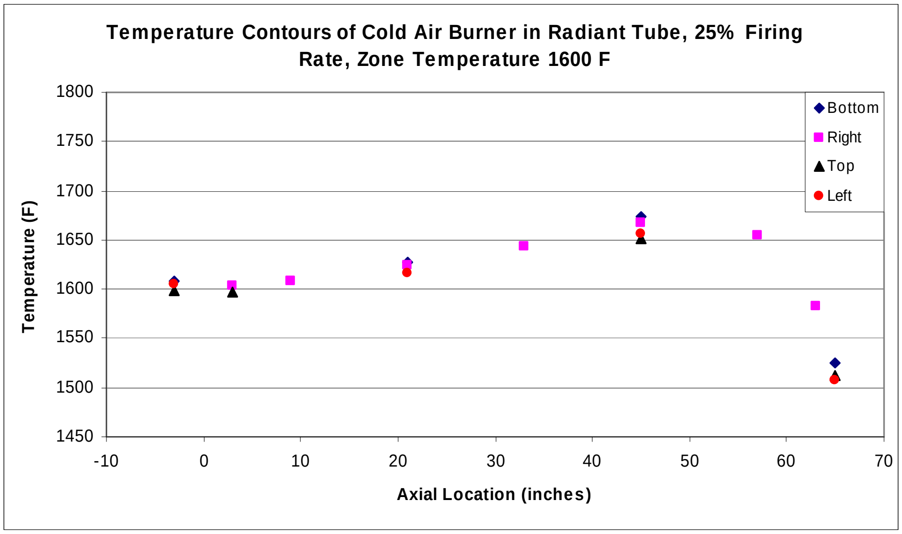
- Exhaust Temperature: 1296 °F
- Available Heat: 59 percent

At 100 percent output (0.259 MMbtu/hr firing rate during a 1600 °F zone setpoint), the following combustion performance metrics were recorded:

- O_2 in Exhaust: 3.0 percent
- CO (@ 3 percent O_2): 57.8 ppmv
- NOx (@ 3 percent O_2): 117.6 ppmv
- Exhaust Temperature: 1700 °F
- Available Heat: 49 percent

The high CO levels recorded at high fire were stable throughout each of the tests and trended upwards with an increase in temperature and firing rate. Other baseline performance data was also recorded, but the conditions described above will serve as the basis for comparison between the cold air burners, fired without recuperation, and the RASERTs.

The radiant tube of this burner was equipped with lines of thermocouples positioned along the top, left, bottom, and right sides of the tube. The temperature of each thermocouple was also recorded, under the same conditions described above. The temperature profiles along each side were plotted and are shown below. From the perspective of the plots, the cold-air burners were fired from right to left; combustion began somewhere near the 60-inch axial location, and the exhaust left the radiant tube at the -10-inch axial location. RASERT units were installed in the same type of radiant tubes, but with the burner located at the opposite end of the radiant tube.



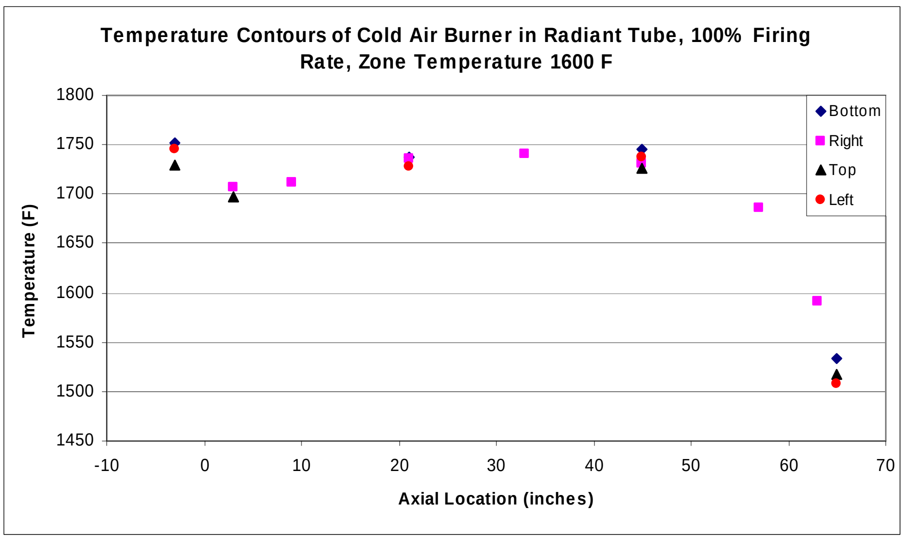


Figure 22. Temperatur contours of radiant tube fired with conventional cold air burner: 25 percent firing rate (top) and 100 percent firing rate (bottom); thermocouples at axial locations over 60 inches were inside furnace wall

Source: Gas Technology Institute, 2008

3.5.2. Field Test

On July 7th, 2008, the site visit to California Steel Industries occurred, to carry out the field test involving the RASERT retrofit of Zone 6. GTI personnel involved consisted of Martin Linck, PhD, Walter Kunc, Aleks Kozlov, PhD, and Harry Kurek. John Wray, and Bill Smith represented CSI during the field test. A schematic diagram of Zone 6 is shown in Figure 23.

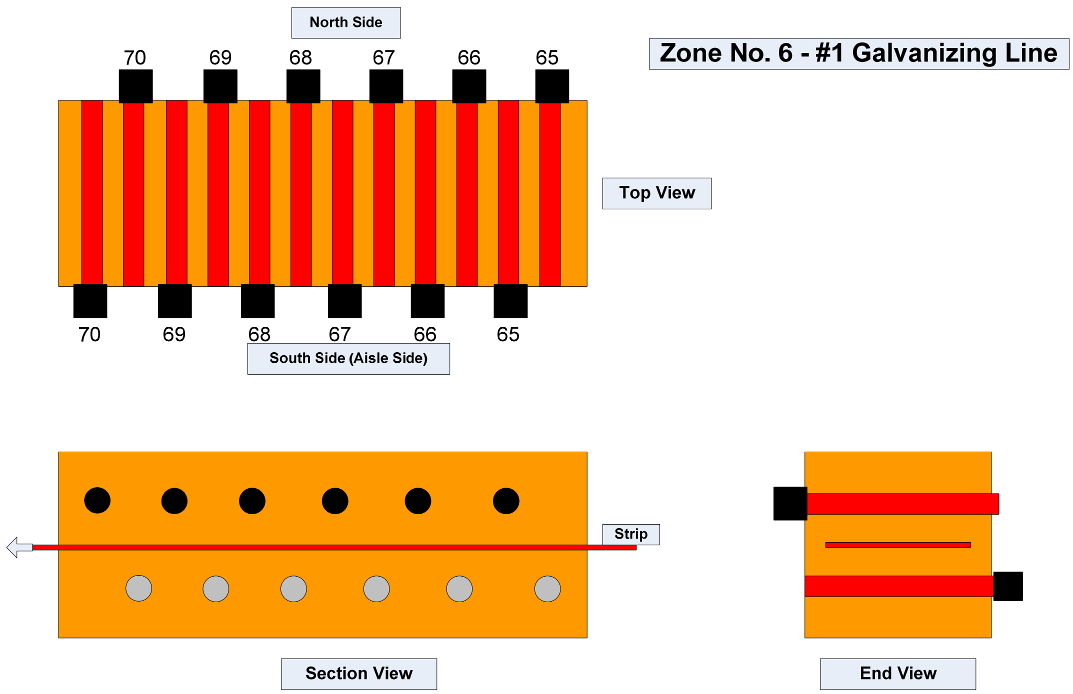


Figure 23. The layout of Zone 6 is shown in the sketch above

Source: Gas Technology Institute, 2008

The purpose of the test was to set up data acquisition equipment to monitor retrofitted RASERTs in Zone 6, and to carry out the following:

- Record exhaust temperatures of exhaust streams from 12 RASERTs in Zone 6 using non-aspirating thermocouples
- Record Radiant tube temperatures from 24 thermocouples installed on the radiant tube of No. 69 South burner (of the 24 thermocouples installed, only 12 provided useful data during the field test)
- Record firing tube temperatures from six thermocouples installed on the firing tube of the No. 69 South burner
- Record the true temperature of the exhaust stream associated with the No. 69 South burner using an aspirated thermocouple
- Monitor and record the emissions generated by No. 69 South burner and No. 69 North burner
- Monitor the natural gas flow rate associated with both north and south burner banks using pressure transducers attached to metering orifices on the fuel line feeding each bank of burners
- Acquire data with the zone at several operating temperatures between 1400 °F and 1600 °F, and monitor burner operation at 25 percent, 50 percent, 75 percent, and 100 percent

firing rates at each temperature (ultimately, data was taken with the zone near 1400 °F, 1500 °F, and 1600 °F). When the firing rate was not being set manually, the furnace was allowed to operate under automatic control at each temperature.

  - The maximum firing rate of the RASERTs at CSI (at 100 percent) was 138,500 Btu/hr. (MODEL 4748-600 RASERT is rated at 0.14MMBtu.hr)

- Document RASERT installation and piping arrangement with photographs

3.5.3. Summary of Field Test

GTI personnel were on site by July 8. No. 1 galvanizing line at CSI had been brought back up to production on June 30th, and the twelve RASERTs retrofitted in Zone 6 had been tuned at that time by NAMCO. The GTI team (Martin Linck, Walter Kunc, Aleksandr Kozlov and Harry Kurek) spent the first few days of the field test setting up the data collection equipment. Data collection began on Thursday, July 10th. A full 24-hour period of data was collected between Thursday and Friday. On Thursday, the furnace was operated at the predetermined conditions in order to provide useful data for comparison with the baseline tests carried out in February of 2006. The equipment was broken down and removed on Friday, July 11th. The most important process variable from the perspective of CSI is the temperature of the strip as it leaves Zone 7. Other process variables, including the zone temperature in Zone 6, can vary considerably without adversely affecting production, as long as the temperature of the strip leaving Zone 7 is in the correct range. An advanced, automated control system determines the firing rates of burners in each of the seven furnace zones, in such a way that the desired final strip temperature is achieved. Since the firing rates of burners in other zones could be adjusted to compensate for changes made to the firing rates of the burners in Zone 6, the team at the site had considerable latitude, and was able to explore a wide variety of zone operating conditions during the test. A day-by-day narrative of the test follows.

07/07/08 Monday: With assistance from CSI (Bill Smith and John Wray), the GTI principal investigator (Dr. Martin Linck) became familiarized with the layout of the galvanizing line, and inspected the RASERTs in Zones 6 and 7. All looked satisfactory, with the exception of No. 67 South (in Zone 6) and No. 71 South (in Zone 7) which were visually observed to have glowing recuperators. This issue would be addressed in depth later in the week. All the experimental test equipment shipped by GTI had arrived in good order. A space in a safety area, under the galvanizing line, had been made available by CSI for the test, and Dr. Linck began setting up the data acquisition system and exhaust gas analyzer. However, nitrogen bottles and sample gas needed for calibration of the analyzer had not arrived at CSI, necessitating locating the bottles and arranging expedited delivery. Aleks Kozlov and Walter Kunc arrived on site the following day and joined Martin Linck in preparing to carry out the field test.

07/08/08 Tuesday: GTI personnel continued setting up the remaining required equipment. Thermocouples were inserted into the RASERT exhausts in Zone 6 and sampling probes were inserted into the exhausts of the North and South No. 69 burners. The aspirated thermocouple, and the condensers, traps and pumps for the aspiration system, were installed on the No. 69 South burner. Lead wires for all the thermocouples involved in the test were strung from the data collection system at floor level up to the top of the furnace, a distance of 50 feet or so. Gas bottles for the analyzer had not yet been delivered by the vendor.

07/09/08 Wednesday: GTI Personnel focused on labeling the thermocouples and connecting the pairs of leads to the remote data acquisition system three levels below the annealing furnace. The pressure transducers were also connected, and the aspiration system for the aspirated thermocouple was tested. The gas bottles were delivered to the plant at mid day. By the end of Wednesday, the data collection system was operational, and the gas bottles were in place. A discussion was initiated with NAMCO regarding the No. 67 South and No. 71 South burners, and the fact that their recuperators visually appeared operating hotter than normal. The castings around the exhaust pipe were also hotter on these RASERTs; other RASERT bodies displayed temperatures of approximately 600 °F - 700 °F, but the two burners in question were hotter by 100 °F to 200 °F. It became apparent that a full 24 hours worth of data could not be collected, as CSI had to shut down production at 10:30 pm due to product supply problems upstream of the galvanizing line. In order to gather data in the afternoon, prior to the line shutdown, data was taken with the furnace at 1500 °F; and Zone 6 was manually set to 25 percent, 50 percent, 75 percent, and 100 percent fire. It was then noted that the O_2 readings in the sample being taken from No. 69 South burner were slightly higher than expected; John Wray proposed that burner No. 69 South be tuned using a handheld analyzer, on the assumption that the burner settings were off-calibration. This analyzer then revealed that the burner settings were correct (all burners had been tuned to 4 percent O_2) and that there was a leak in the exhaust gas analyzer. Several hours were required locating the leak, and a repair was effected. Arrangements were made for the plant technician to shut down data acquisition when the steel supply ran out (This occurred around 10:30 pm). A meeting and conference call, involving Terry Stepanski (NAMCO), Harry Kurek, Martin Linck, Walter Kunc, Aleks Kozlov, John Wray and NAMCO personnel in Cleveland was scheduled for the following day, to discuss No. 67 South and No. 71 South burners.

07/10/08 Thursday: GTI personnel arrived prior to the galvanizing line start up for purposes of conferring with NAMCO personnel in Cleveland regarding the hot-running RASERTs (No. 67 South and No. 71 South). A decision was made to examine No. 67 South and No. 71 South in detail; i.e., the flows of natural gas and the O_2 percentages in the exhaust stream associated with each RASERT would be checked, and any needed corrective action would be taken. The plant resumed production at approximately 1:30 pm; GTI and CSI physically checked the gas flows and O_2 percentages on all the RASERTs in Zone 6 and Zone 7. The two hot burners were found to be properly adjusted; they displayed the same firing rates and O_2 percentages as the other burners in each zone. The visual difference in the appearance of the recuperators on these burners, seen through the viewport in the burner bodies, was noted by the team. These two RASERTs had a visible orange glow near the far end of the recuperator (in the vicinity of the crossover) whereas other RASERTs in the two zones had recuperators that were not visibly glowing. Two possibilities were proposed: short circuiting (wherein unburned fuel was passing back into the recuperator without combusting in the combustion annulus) and excessive flue gas recirculation (FGR), which might delay combustion so severely that combustible material was returning to the recuperator. It was later found, on 08/06/08, that short circuiting, due to faulty positioning of the firing tube, was the cause of the overheating. On 07/10/08, it was determined that the two RASERTs would be taken out of service, and the problem corrected as soon as practicable. GTI personnel requested that the furnace operating temperature be set to 1500 °F, data was retaken, and the furnace was reset to approximately 1400 °F. Data was taken at 1400 °F; then the furnace temperature was ramped up to approximately 1600 °F; and data was taken at this temperature, as well. The data acquisition system was left running overnight in order to gather 24 hours of data.

07/11/08 Friday: The data acquisition system was checked in the morning, to ensure that data had been gathered successfully during the night. GTI personnel returned to the plant and checked the emissions from No. 68 South (in addition to those that had been acquired from No. 69 South and No. 69 North) and switched out the aspirated thermocouple installed in burner No. 69 South. Up to this point all data from the aspirated thermocouple had been gathered using an aspirated thermocouple assembled by NAMCO. The readings returned by said thermocouple were compared with readings returned by an aspirated thermocouple provided by GTI. Both aspirating thermocouples returned equivalent readings. The gas sampling line on the south side of the furnace was briefly positioned in the No. 68 South burner, to provide a broader basis for comparison. The shutdown of the data acquisition system was begun, and the teardown of the data acquisition equipment was carried out. The equipment was boxed up and readied for shipment to GTI, and remaining GTI personnel left the plant at the conclusion of the day shift. CSI made arrangements to ship the equipment back to GTI the following week.

The following equipment was utilized in the course of the field trial at CSI:

- The fuel gas pressure regulator was a NAMCO 7216-0 B 1/04 Variable Ratio Air/Gas Ratio Regulator
- Orifice on the natural gas line: NAMCO 4-3311/8697-1; 1"; orifice size 810. (There are two orifices. One orifice measures the gas flow to the six, south RASERTs and the second orifice measures gas flow to the six north RASERTs.)
    - Reading: Based on manufacturer specifications, 4.1 in.w.c. drop ≈ approximately 866 scfh natural gas. However, in practice, the pressure drop across these orifices was approximately 2.5 in. w.c. when the zone

was at high fire. The discrepancy was likely due to non-idealities in the gas flow through the orifice; in any case, checks of gas flows through the individual burners indicated that the flowrates of gas to each burner at low and high fire were correct.

  - The orifice bodies were equipped with quick-connect tube fittings, but these were found to be unreliable, and were replaced with tubing connectors, instead.

Data collection:

- Table, chairs, and power extension with multiple outlets
- Data logging computer system; was equipped with 48 thermocouple inputs and eight analog inputs.
- Horiba PG-250 portable gas analyzer (connected to data acquisition computer via an RS 232 connection).
- Calibration gases for O_2, CO_2, CO, NOx—Due to logistical issues, the gases did not arrive until the second day of the site visit.
- Two nitrogen tanks to dry the gas sample before it entered the analyzers.
- Regulators for calibration gases and nitrogen tanks.
- Aspirating thermocouple was shipped from NAMCO in Cleveland to GTI; GTI brought a backup thermocouple.
- Aspirating pump (4-chamber, ¾ horsepower) and cooling line for aspirating flow from the thermocouple provided by GTI
- Aspiration train included a cooled stainless steel trap (built by NAMCO), a second trap for liquid water, and a long, flexible 1" ID hose, as well as enough copper tubing and fittings to connect the various components
- Contact thermocouple (type K) and handheld reader (GTI)
- ¼"stainless tubing and sampling lines for gas samples
- Two digital pressure transducers and signal wire to relay signal to data acquisition system
- These pressure transducers were used to monitor the pressure drop across each of the gas metering orifices on the gas lines feeding the north and south burner banks.
- Handheld radios for communication between data acquisition room and top of furnace (provided by CSI)

- These handheld radios were essential when the thermocouples were being connected to the data acquisition system, since the signal wires leading up to the top of the furnace had to be labeled, connected to the correct thermocouple, and detected by the data acquisition system at ground level

- Complete field toolbox
- Digital camera
- Digital manometer with range to 30 in. w.c.
- Four slack-tube manometers as backup
- 1/4” and 1/8” hose barbs, in the event tubing connections could not be made to the gas metering orifices
- 3/8”and 1/4" tygon tubing to mate the manometer to hose barbs
- In the course of the test process data and zone conditions were noted in the GTI lab notebook.

3.5.4. Results

The most useful data were obtained during the period beginning Thursday afternoon (07/10/08), and ending Friday afternoon (07/11/08). During this period, the exhaust gas analyzer was working satisfactorily, and the furnace was running product. Except for some thermocouples on the radiant tube of the No. 69 South RASERT (which had failed due to furnace conditions), all thermocouples were connected and reporting data. Of the 24 radiant tube thermocouples originally installed, ten were reporting useful data during this period.

The thermocouple data is presented in the figures below.

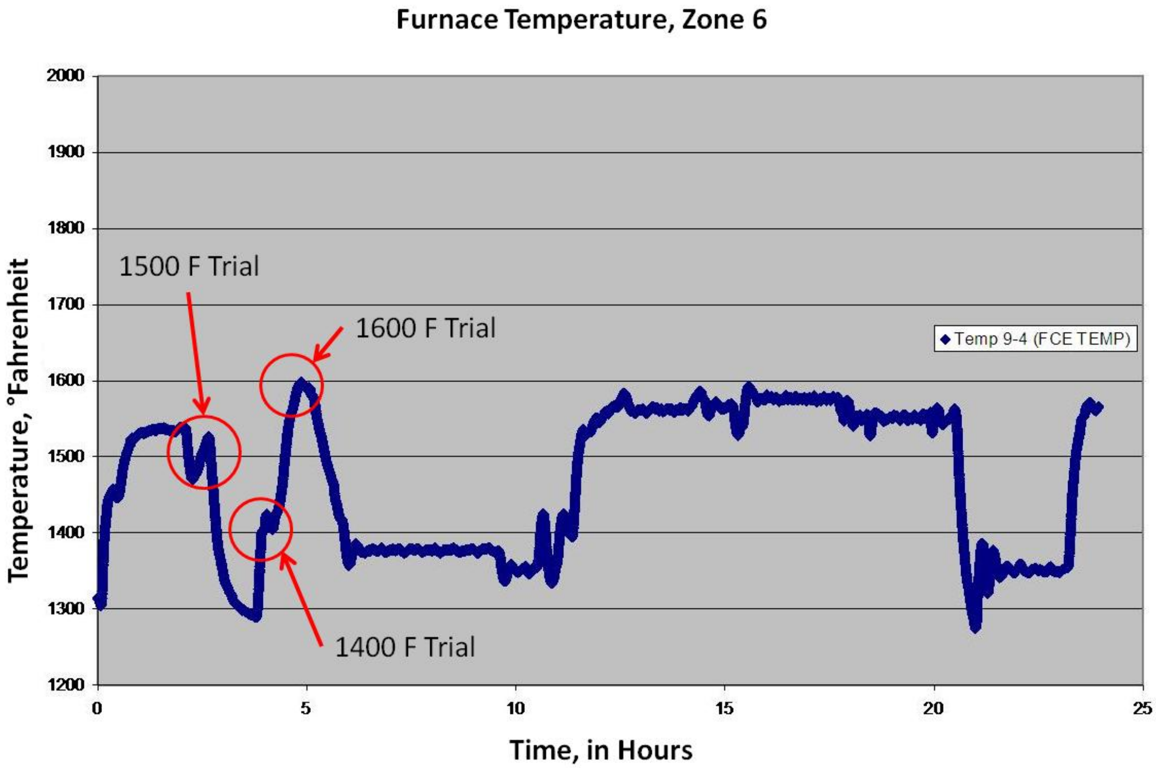


Figure 24. The zone temperature in Zone 6

Source: Gas Technology Institute, 2008

Note the periods when the zone was manually controlled to maintain temperatures of 1400 °F, 1500 °F, and 1600 °F. Since 25 percent, 50 percent, 75 percent and 100 percent firing rates were examined at each zone temperature, the temperature drifted somewhat during these trials, but the temperature remained stable enough to allow comparisons of RASERT behavior at each firing rate. The time is given in hours elapsed since the start of data collection; in this case data collection began at 1:25 pm on Thursday, 07/10/08.

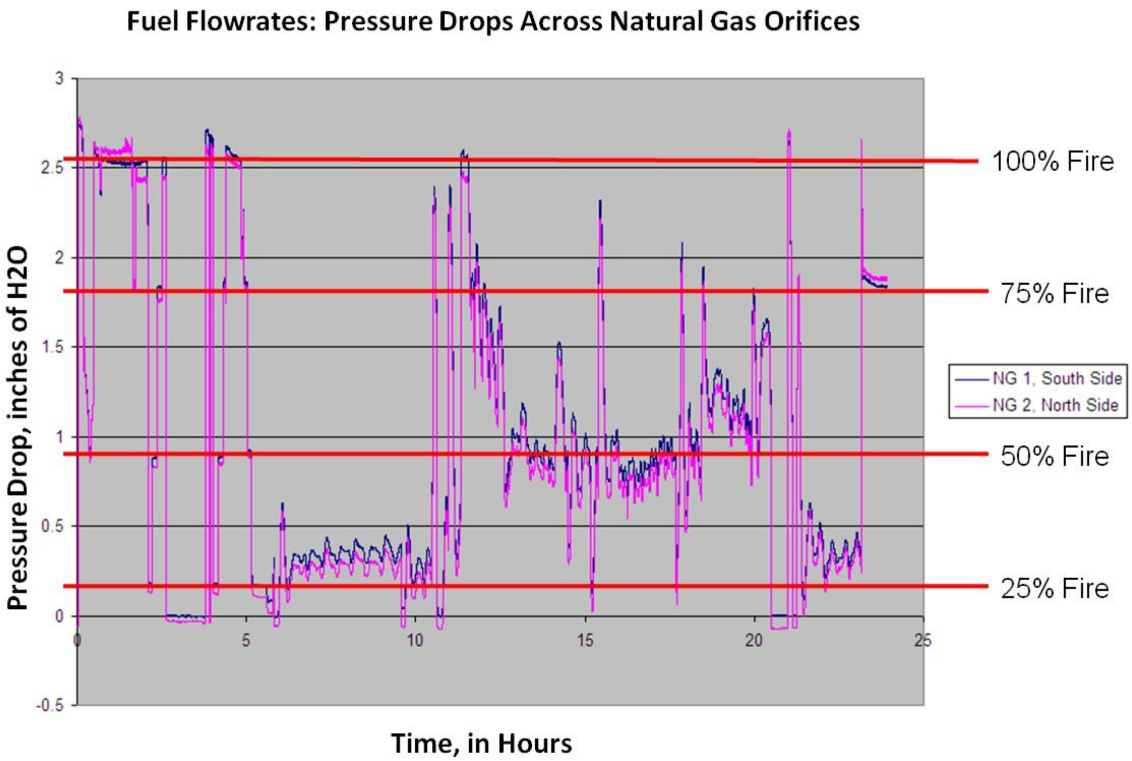


Figure 25. Pressure drops across natural gas orifices on main natural gas lines supplying the north and south banks of burners

Source: Gas Technology Institute, 2008

The pressure drops corresponding to 25 percent, 50 percent, 75 percent, and 100 percent firing rates are indicated, and periods when the zone was manually held at each firing rate are seen. The zone was under automatic control from the 5th to the 23rd hour of the test. During the 23rd hour of the test, the zone was set to the 75 percent firing rate, and was kept there until the end of data acquisition.

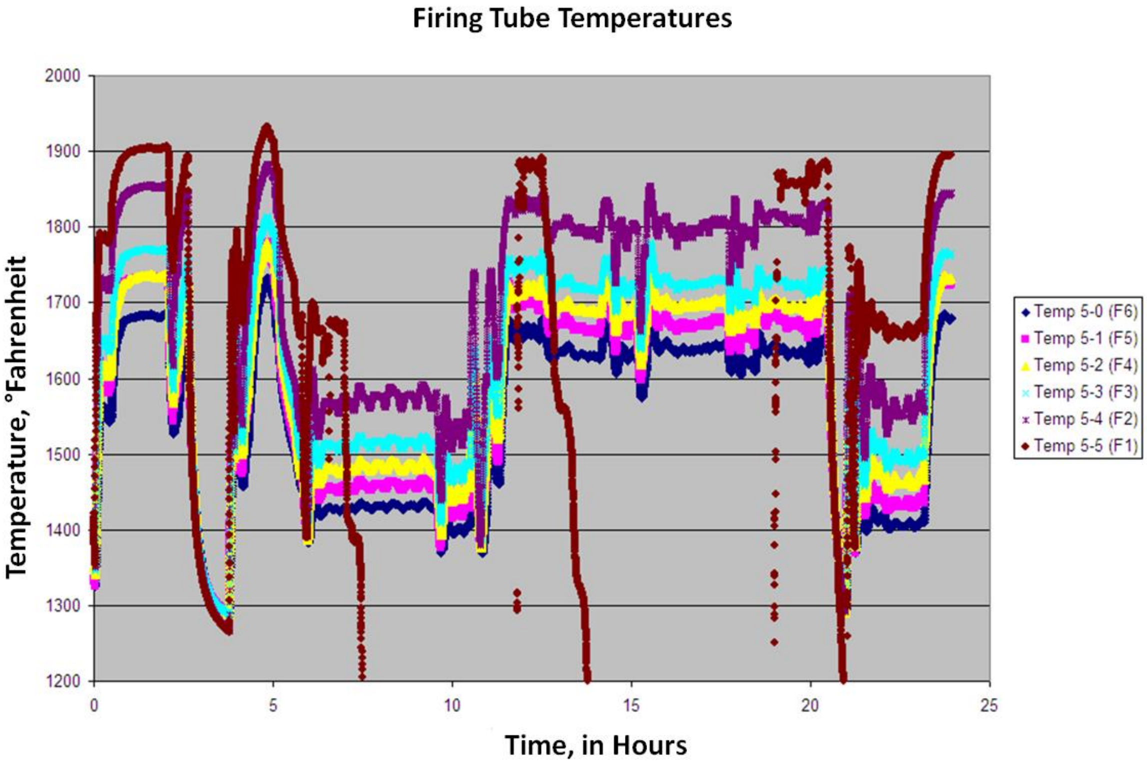


Figure 26. Firing tube temperatures, recorded by the six thermocouples on the firing tube

Source: Gas Technology Institute, 2008

During the test Temp 5-5 (here 5-5 indicated the data channel on which the signal was being received by the data acquisition system), showing the temperature of thermocouple F1, became unreliable after the 6th hour of the test, and appears to have transmitted the correct temperature only intermittently. However, the thermocouple worked well during the periods when the burners were being controlled manually at the three furnace temperatures. The F1 thermocouple position is closest to the burner end of the firing tube, and is positioned in line with one of the fuel ports of the burner. As a result, this is the most critical firing tube thermocouple location, since it is exposed to the highest temperature.

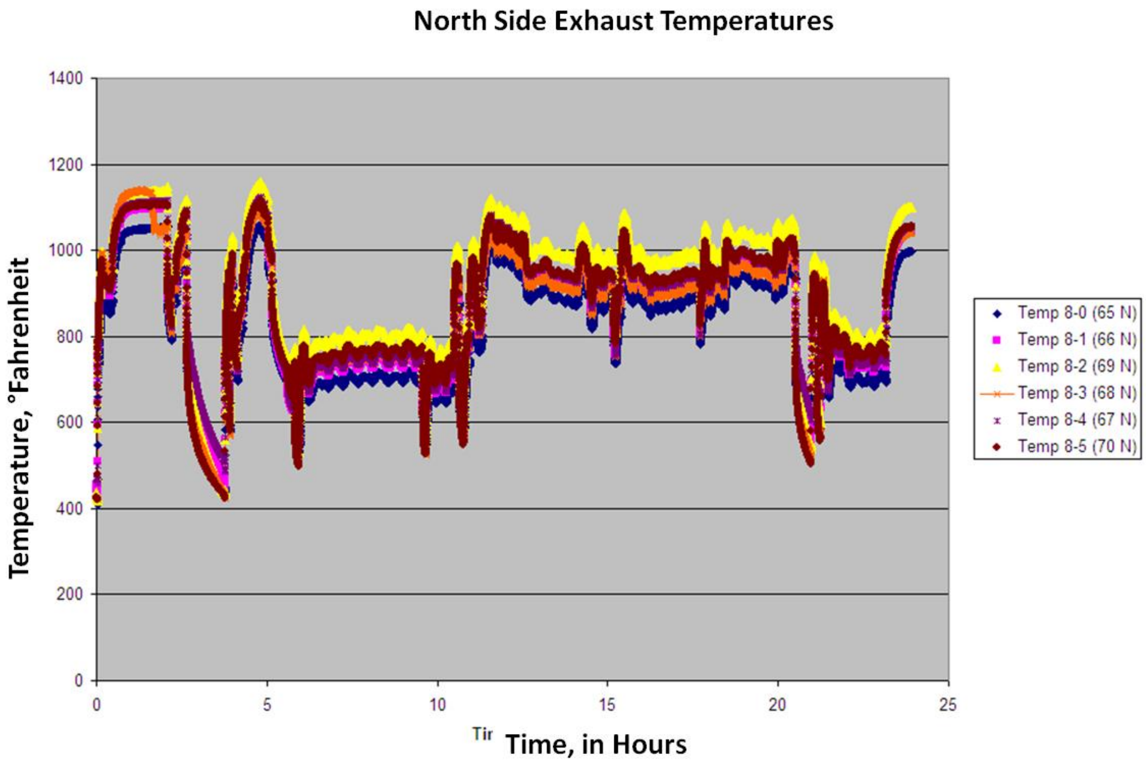


Figure 27. Exhaust temperatures, reported by the thermocouple inserted down the exhaust tubes of the six north side burners

Source: Gas Technology Institute, 2008

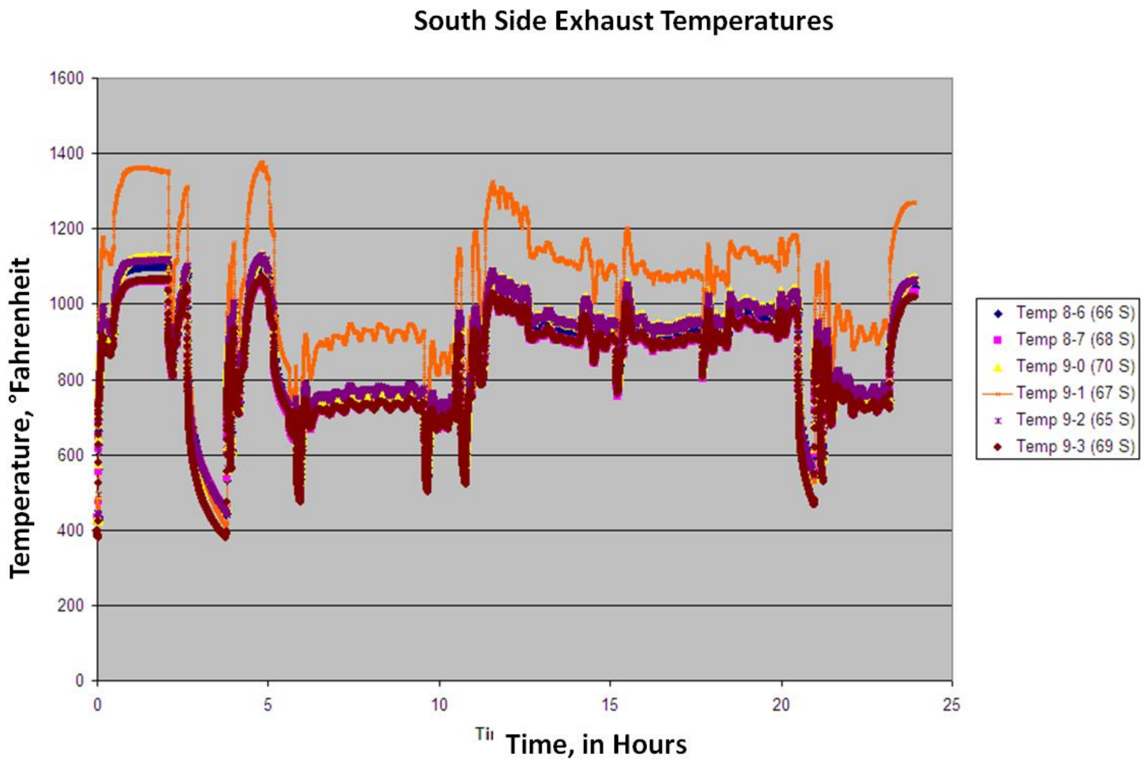


Figure 28. Exhaust temperatures, reported by the thermocouples inserted down the exhaust tubes of the six south side burners

Source: Gas Technology Institute, 2008

Note that the temperature of the exhaust associated with burner 67 S is considerably hotter than the other burners in this group. When visually inspected, this burner was found to show a glowing recuperator. The firing tube was not properly seated in the recuperator, which allowed combustible gas and air to short-circuit, bypassing the combustion annulus and returning directly to the recuperator, where combustion occurred. This problem was readily corrected in the field. CSI shut off the affected burners and re-seated the firing tubes in order to establish a proper connection between the firing tube and the recuperator during an outage.

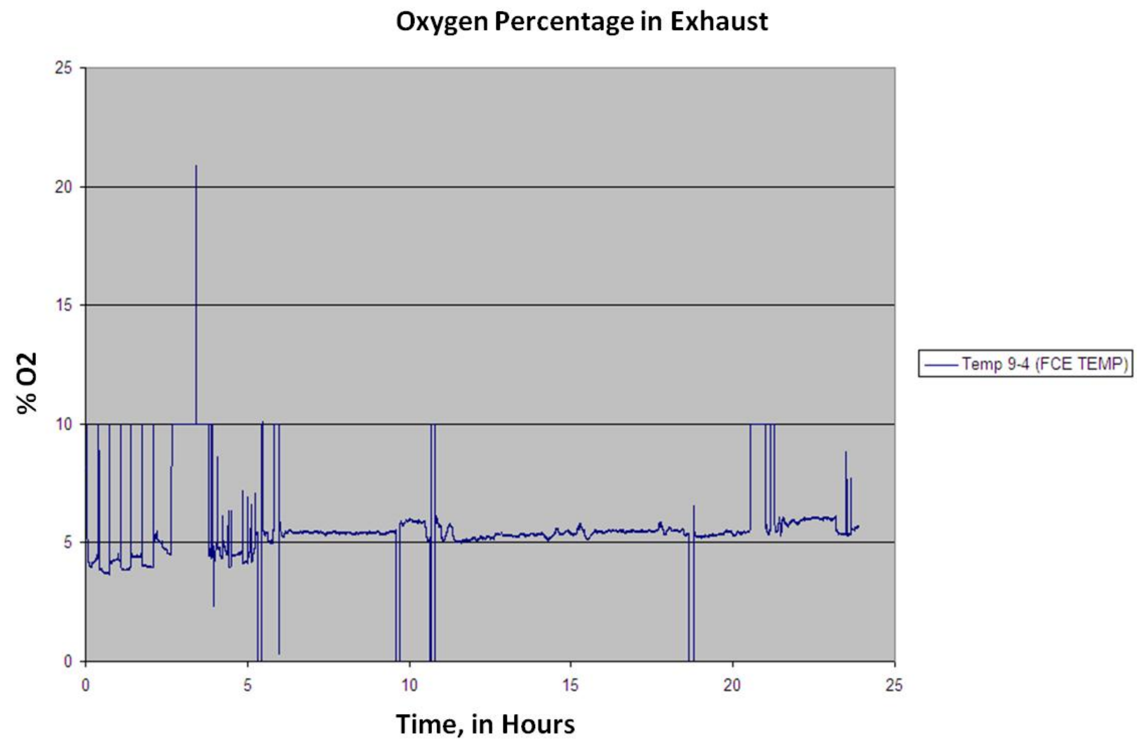


Figure 29. O_2 percentage, recorded in the exhaust of the burners examined during the test

Source: Gas Technology Institute, 2008

This plot (Figure 29) is somewhat erratic due to the gas sampling probe being switched several times from burner 69 S to 69 N during the first three hours of the test, and the firing rate was changed several times. The reading reported by the analyzer defaults to 10 percent O_2 (the maximum of the range) when the O_2 concentration exceeds 10 percent. In general, the O_2 readings during the first five hours were between 4 percent to 5 percent. This was consistent with the corresponding reading reported by a handheld analyzer. Calculations of burner efficiency and performance cited in this report are based on data from the first five hours.

Figure 30, below, shows corrected concentrations of NOx and CO occurring in the exhaust gases. As can be seen from the plots, NOx was relatively stable, but the CO concentrations tended to spike when the burner was re-lit after being shut off, and when the firing rate was increased significantly.

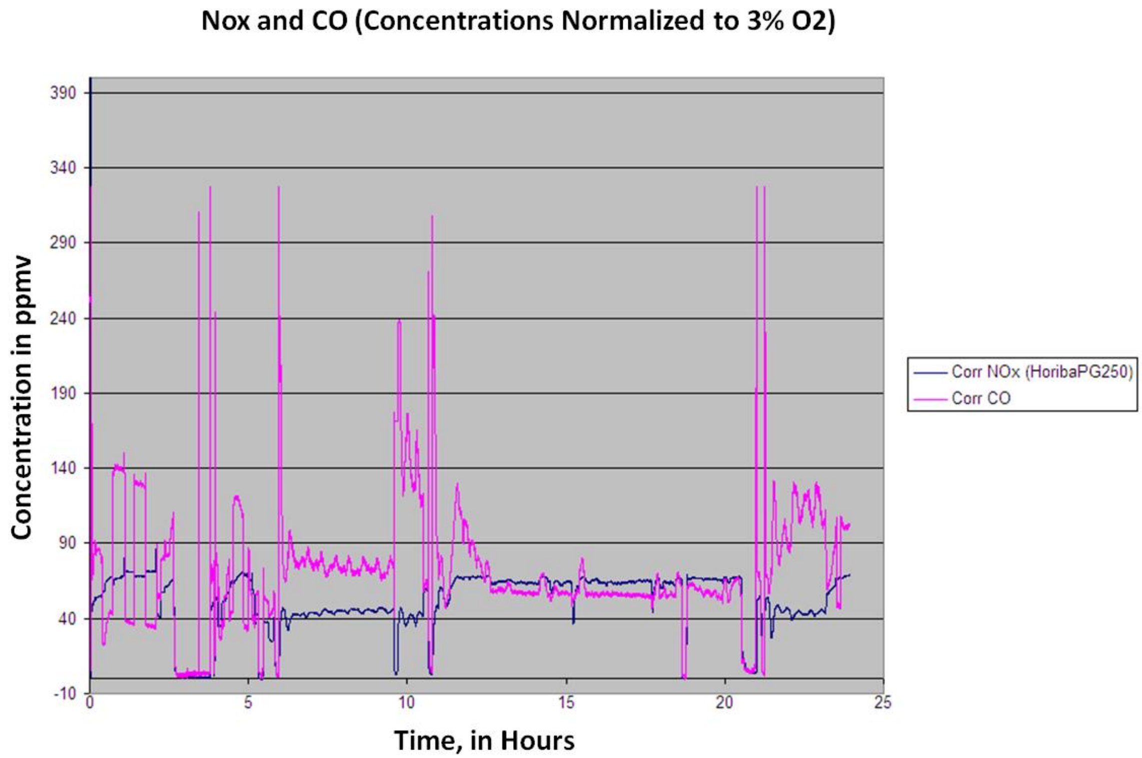


Figure 30. Concentrations of oxides of nitrogen (NOx) and carbon monoxide (CO) in the exhaust gas samples, corrected to 3 percent O_2

Source: Gas Technology Institute, 2008

Table 4, below, shows a summary of RASERT performance, at all four firing rates of interest. All three of the furnace temperatures examined during the field test are shown in the table. The CO concentrations were lower than those seen during baseline testing at the 100 percent firing rate; however, at the 25 percent firing rate, almost no CO was observed in the baseline case, and a significant amount of CO was present at the 25 percent firing rate when the RASERT was examined. The efficiency of the RASERT was much higher, particularly at lower firing rates and lower furnace temperatures. At a furnace temperature of 1400 °F, and a firing rate of 25 percent, the RASERT was over 72 percent thermally efficient.

Table 4. Relevant data showing efficiency and performance of RASERT at various zone temperatures

Source: Gas Technology Institute, 2008

Target Zone Temperature: 1400 °F								
Time	Firing Rate	Zone Temp	Exhaust Temp (Asp. TC)	Corr NOx	Corr CO	CO_2	O_2	Efficiency
5:32:27 PM	25 percent	1413.8536	729.6016	35.3571	27.477	8.45	4.76	72.21 percent
5:42:32 PM	50 percent	1425.8444	858.6412	53.2096	33.277	8.43	4.83	68.42 percent
5:49:31 PM	75 percent	1457.502	970.2552	58.3636	39.077	8.62	4.5	65.58 percent
5:24:57 PM	100 percent	1408.3066	965.6607	53.2212	44.877	8.72	4.36	65.94 percent

Target Zone Temperature: 1500 °F								
Time	Firing Rate	Zone Temp	Exhaust Temp (Asp. TC)	Corr NOx	Corr CO	CO_2	O_2	Efficiency
3:37:32 PM	25 percent	1484.9572	825.6389	41.2117	33.81375	8.19	5.32	68.90 percent
3:44:22 PM	50 percent	1474.7595	915.4008	57.636	35.5725	8.38	5.01	66.60 percent
3:54:47 PM	75 percent	1503.8958	1007.684	62.7624	37.33125	8.56	4.71	64.30 percent
4:03:17 PM	100 percent	1524.7953	1071.3354	66.1091	39.09	8.66	4.5	62.70 percent

Target Zone Temperature: 1600 °F								
Time	Firing Rate	Zone Temp	Exhaust Temp (Asp. TC)	Corr NOx	Corr CO	CO_2	O_2	Efficiency
6:40:02 PM	25 percent	1550.5137	810.8467	43.3887	40.1505	8.19	5.36	69.33 percent
6:29:32 PM	50 percent	1590.0156	991.9953	65.2445	37.868	8.42	4.64	64.46 percent
6:26:32 PM	75 percent	1590.3518	1065.5082	69.3236	35.5855	8.58	4.59	62.68 percent
6:14:27 PM	100 percent	1595.0583	1102.993	70.7261	33.303	8.57	4.61	61.53 percent

Radiant and Firing Tube Thermocouples

Figures 31 and 32 show the location of thermocouples on the radiant and firing tubes, and the manner in which the firing tube and burner are installed in the radiant tube. The axial locations are designated according to the number of inches between each thermocouple and the flame stabilizer plate in the burner. The thermocouples on the radiant tube were installed in rows on the top, right, bottom and left side of the radiant tube. The thermocouples on the firing tube were installed in two rows, with one row on top and one on the right side of the firing tube. On the radiant tube, only 10 of the 24 thermocouples installed provided useful data throughout the test. On the firing tube, the thermocouples were more reliable. Thermocouples on the firing tube were installed in pairs, but the thermocouple in each pair located on the right side of the tube always reported a higher temperature than the thermocouple installed on the top of the firing tube. The reason for this higher temperature reading was that thermocouples at the top of the tube were not directly downstream of the fuel jets emerging from the burner, while the thermocouples on the right side of the firing tube were always exposed directly to combusting material passing through the combustion annulus.

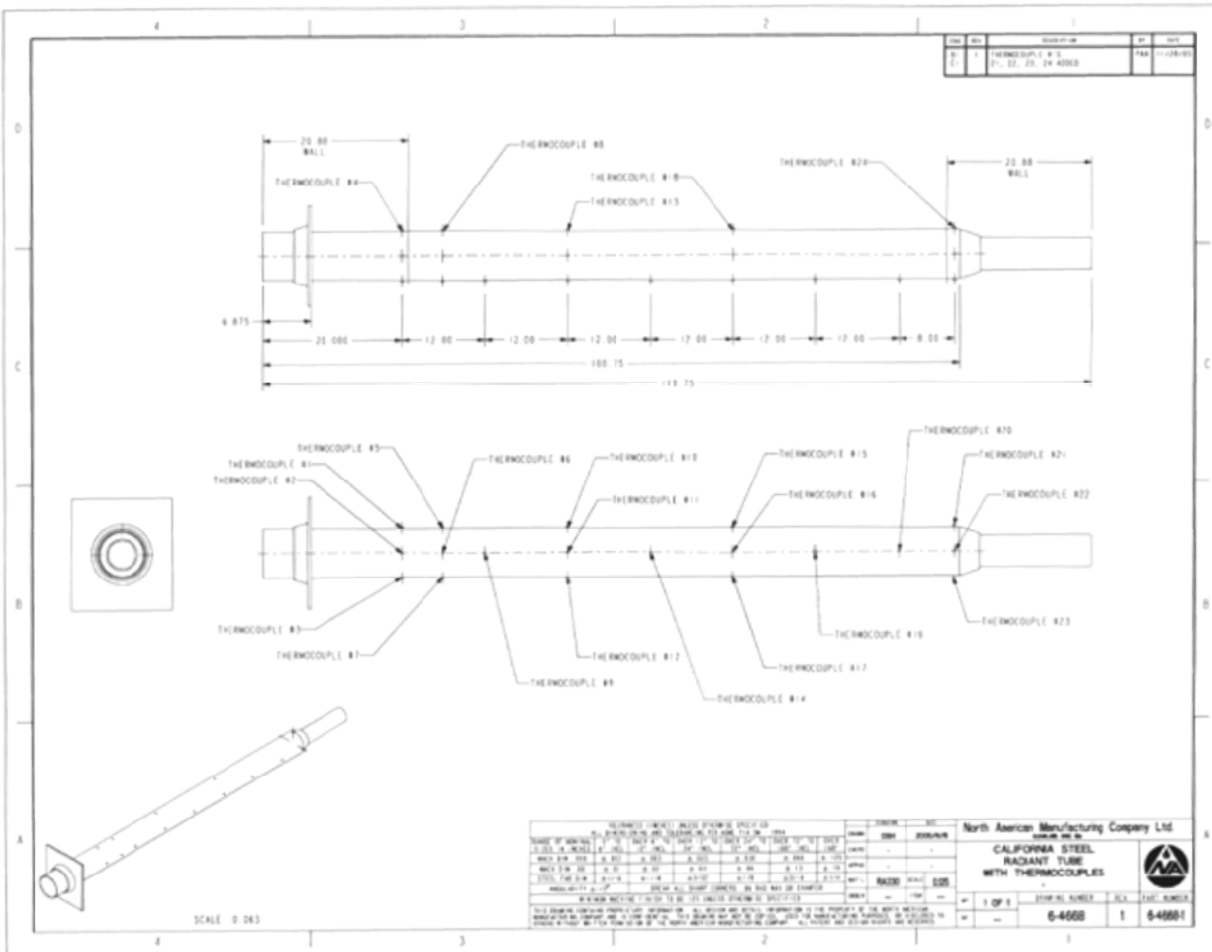


Figure 31. Thermocouple layout on the radiant tube of burner No. 69 South

Source: North American Manufacturing Company, 2008

The axial location of each thermocouple is plotted below, relative to the flame stabilization plate, located halfway between Thermocouple No. 1 and thermocouple No. 5. Thus, thermocouples No. 1, No. 2, No. 3, and No. 4 have an axial location of -3 inches, while thermocouple No. 5, No. 6, No. 7, and No. 8 have an axial location of +3 inches. Thermocouple No. 9 has an axial location of +9 inches. Thermocouples in line with Thermocouple No. 1 are at the top of the radiant tube; those in line with Thermocouple No. 2 are at the right, and so on.

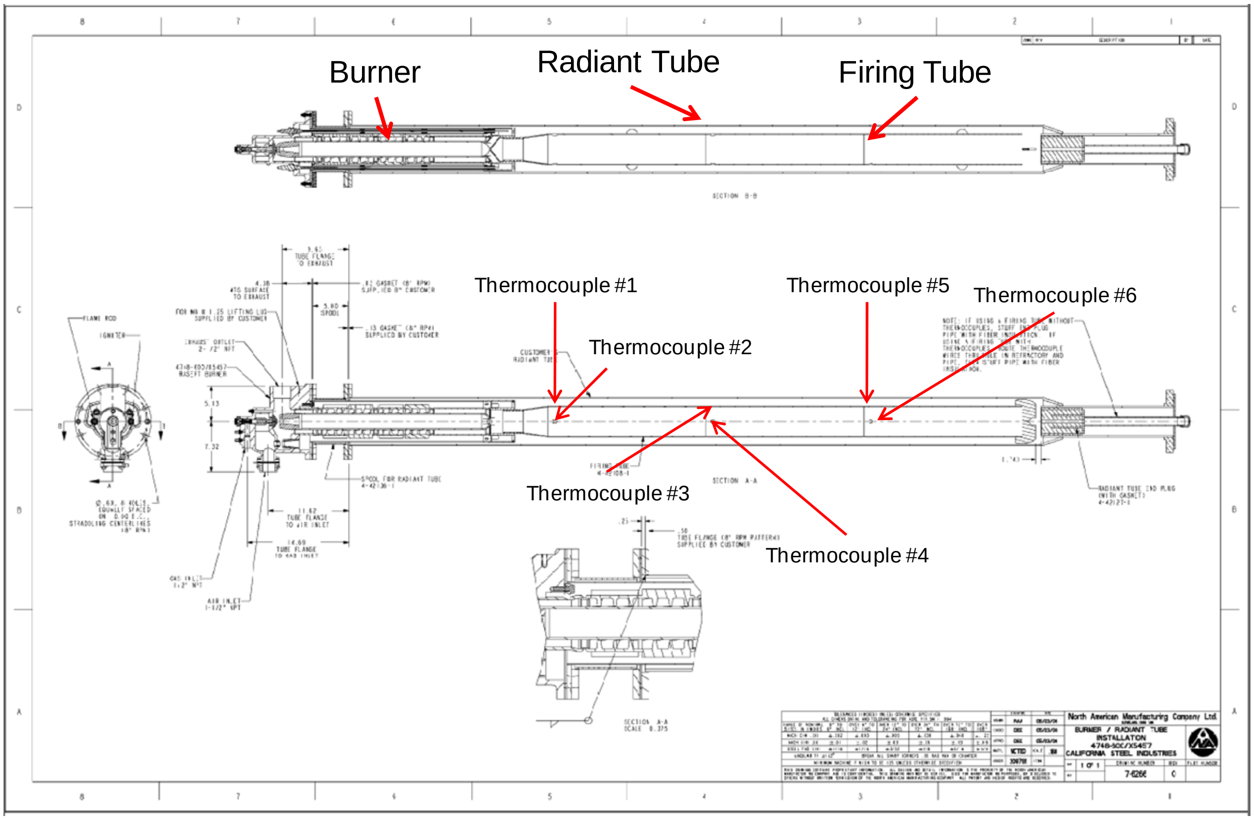


Figure 32. Layout of the firing tube thermocouples, within the RASERT assembly

Source: North American Manufacturing Company, 2008

Temperature Profiles

The temperature profiles along the radiant and firing tubes were plotted using temperature data obtained from the thermocouples installed on each tube. Temperature contours were developed for each of the four firing rates (25 percent, 50 percent, 75 percent, and 100 percent), at each of the zone temperatures described in Table 1 (1400 °F, 1500 °F and 1600 °F). Each plot below shows temperatures along the top, right, bottom, and left side of the radiant tube. In addition, the firing tube temperatures are plotted, and the exact furnace temperature corresponding to each data set is also given.

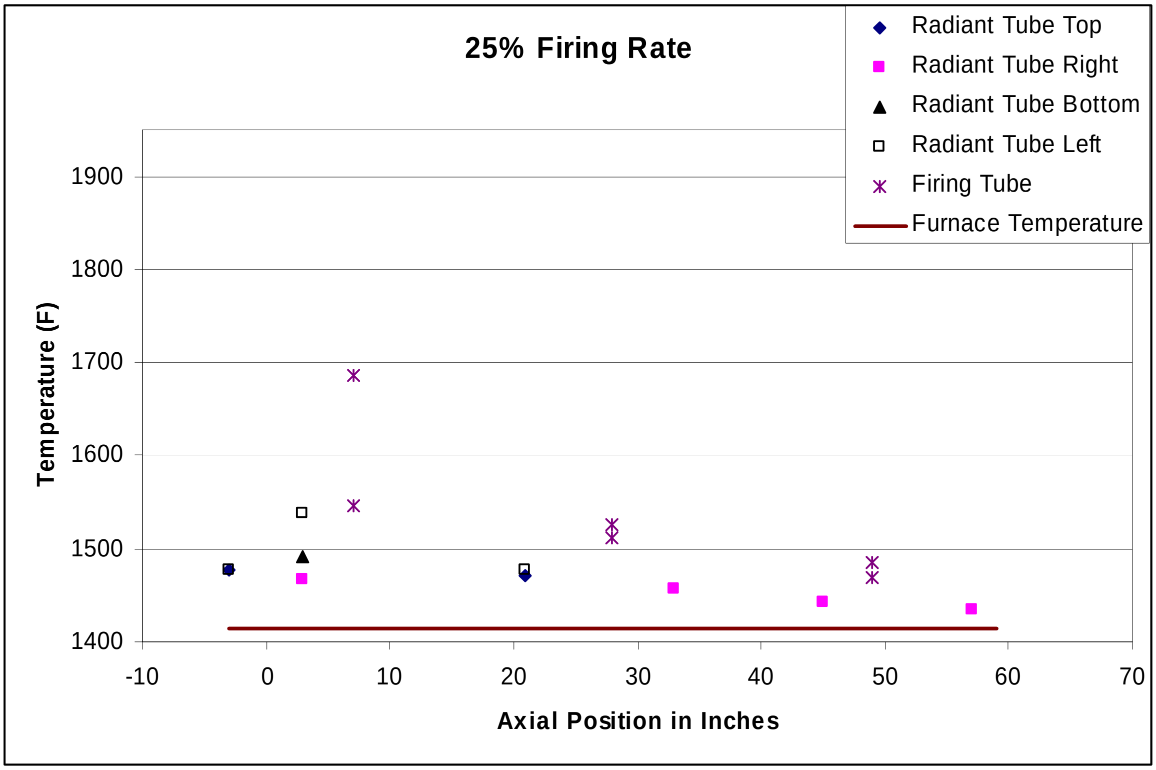


Figure 33. Furnace temperature target 1400 °F, temperature contours at 25 percent firing rate

Source: Gas Technology Institute, 2008

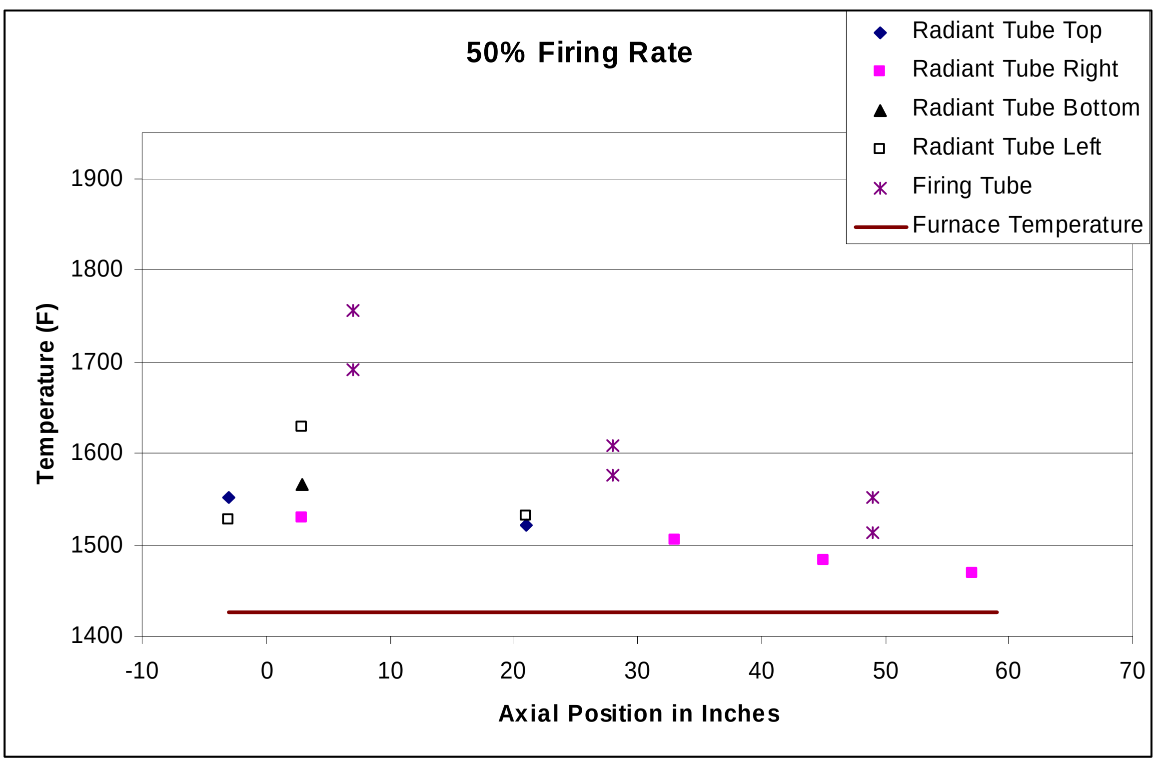


Figure 34. Furnace temperature target 1400 °F, temperature contours at 50 percent firing rate

Source: Gas Technology Institute, 2008

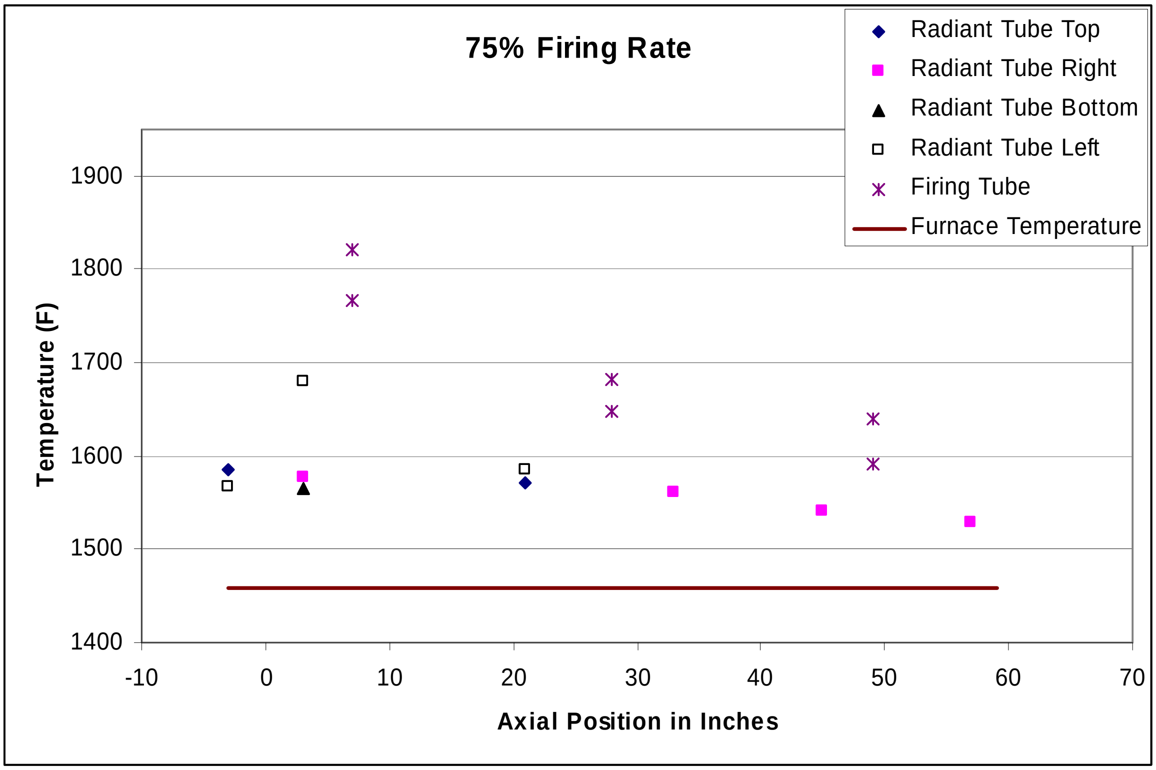


Figure 35. Furnace temperature target 1400 ^oF, temperature contours at 75 percent firing rate

Source: Gas Technology Institute, 2008

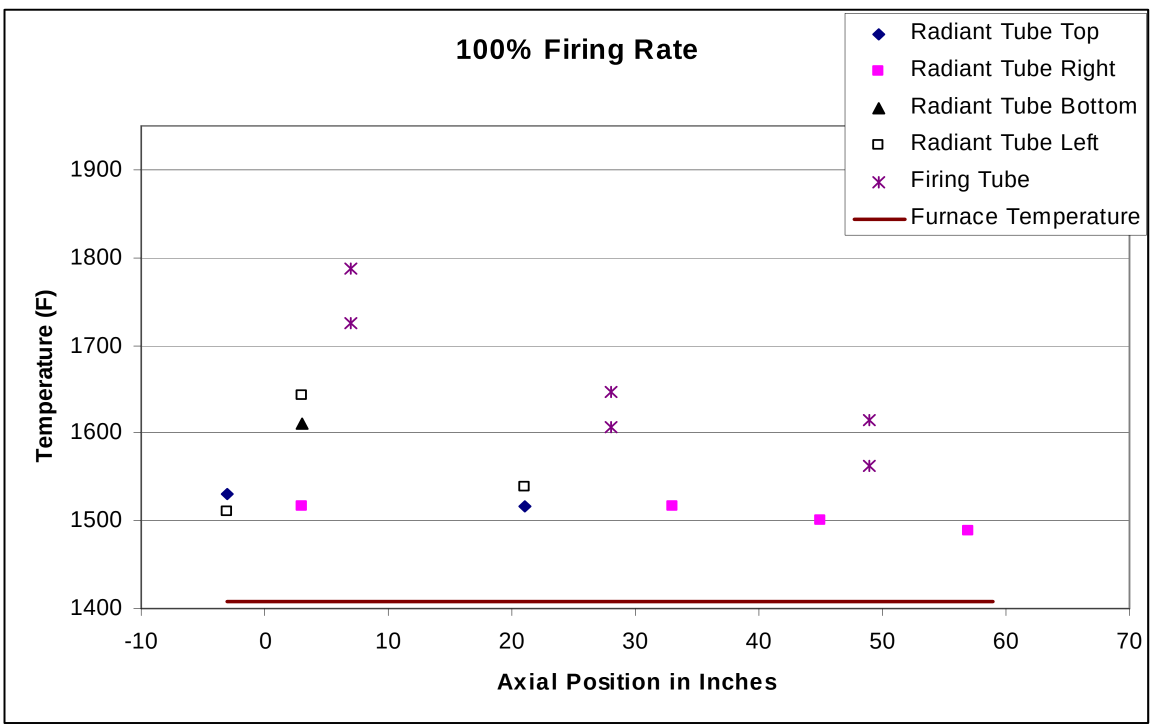


Figure 36. Furnace temperature target 1400 ^oF, temperature contours at 100 percent firing rate

Source: Gas Technology Institute, 2008

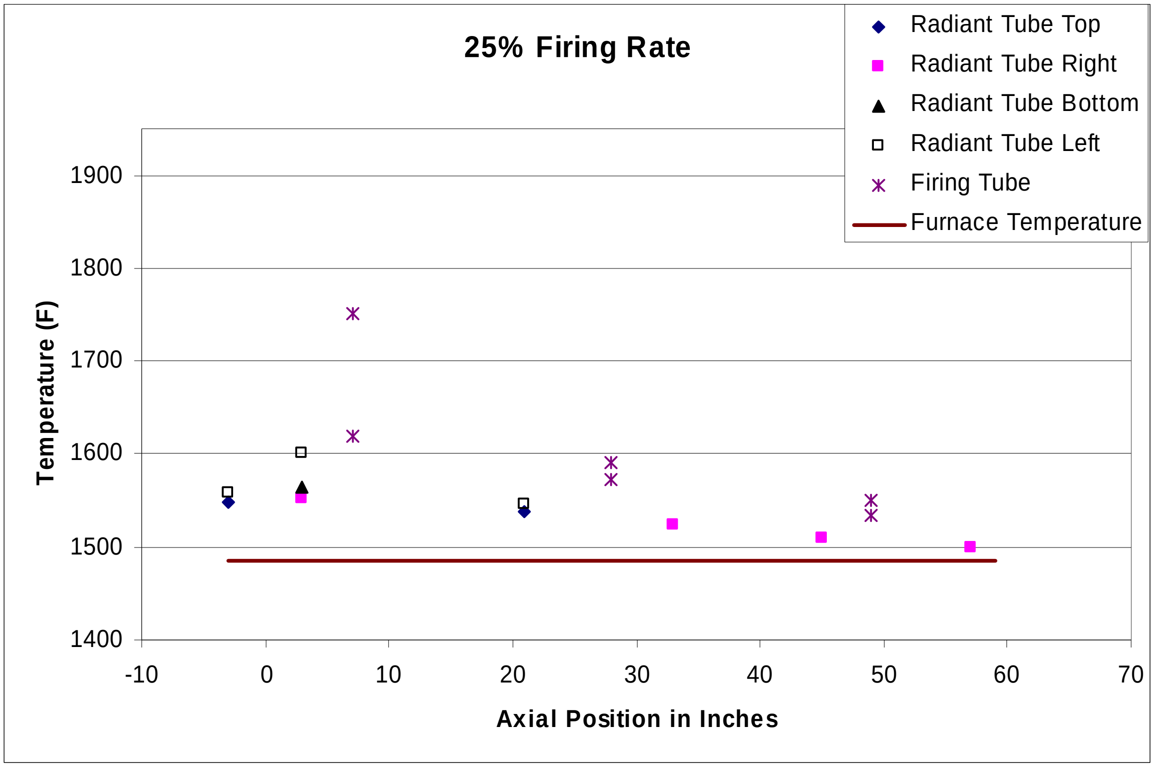


Figure 37. Furnace temperature target 1500 ^{o}F, temperature contours at 25 percent firing rate

Source: Gas Technology Institute, 2008

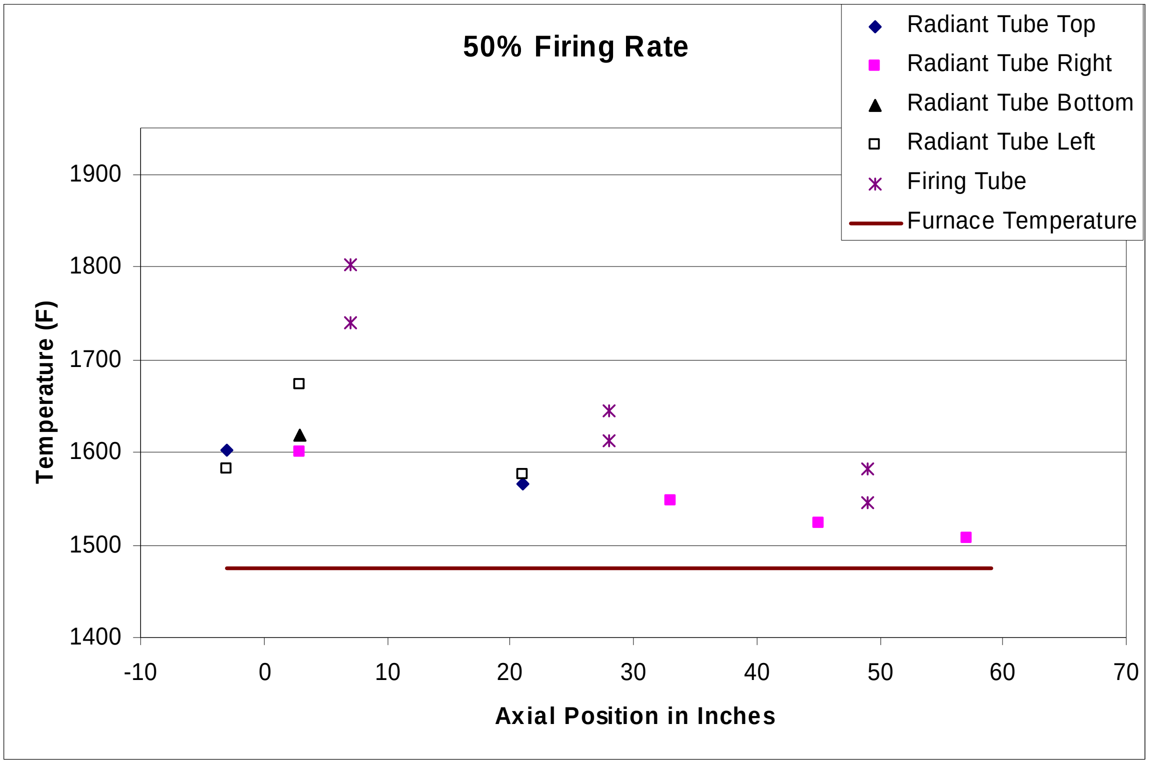


Figure 38. Furnace temperature target 1500 °F, temperature contours at 50 percent firing rate

Source: Gas Technology Institute, 2008

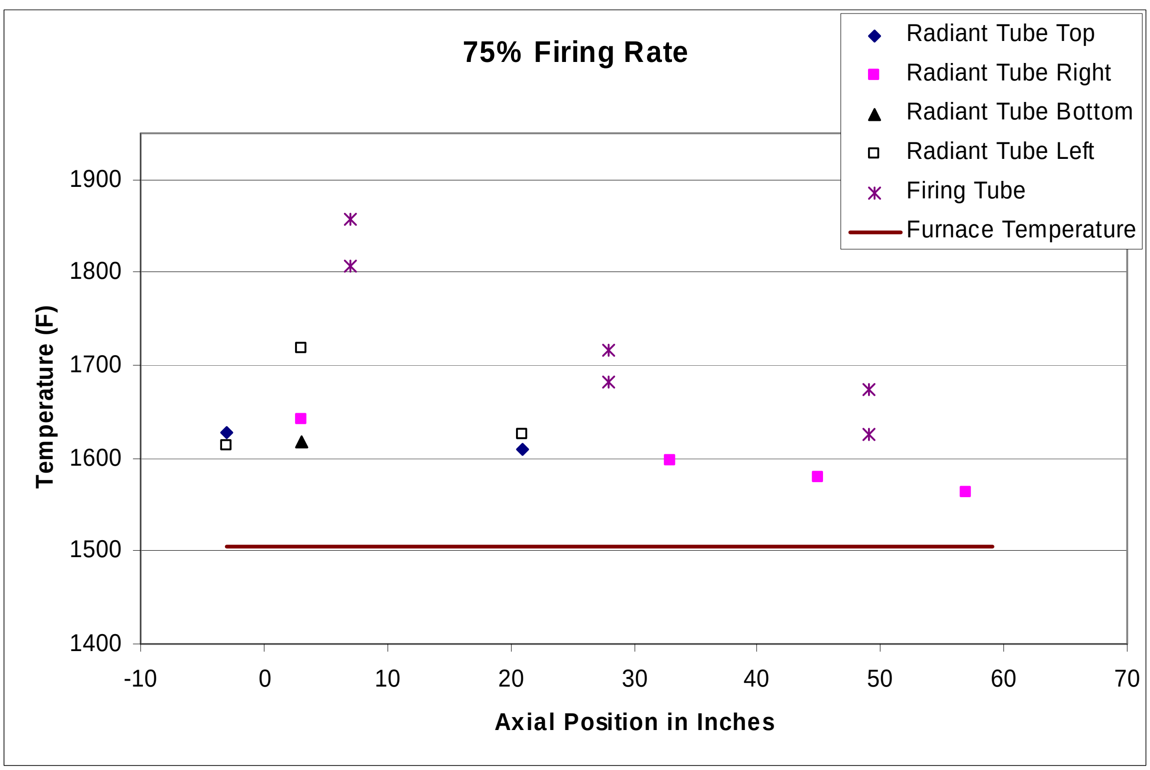


Figure 39. Furnace temperature target 1500 °F, temperature contours at 75 percent firing rate

Source: Gas Technology Institute, 2008

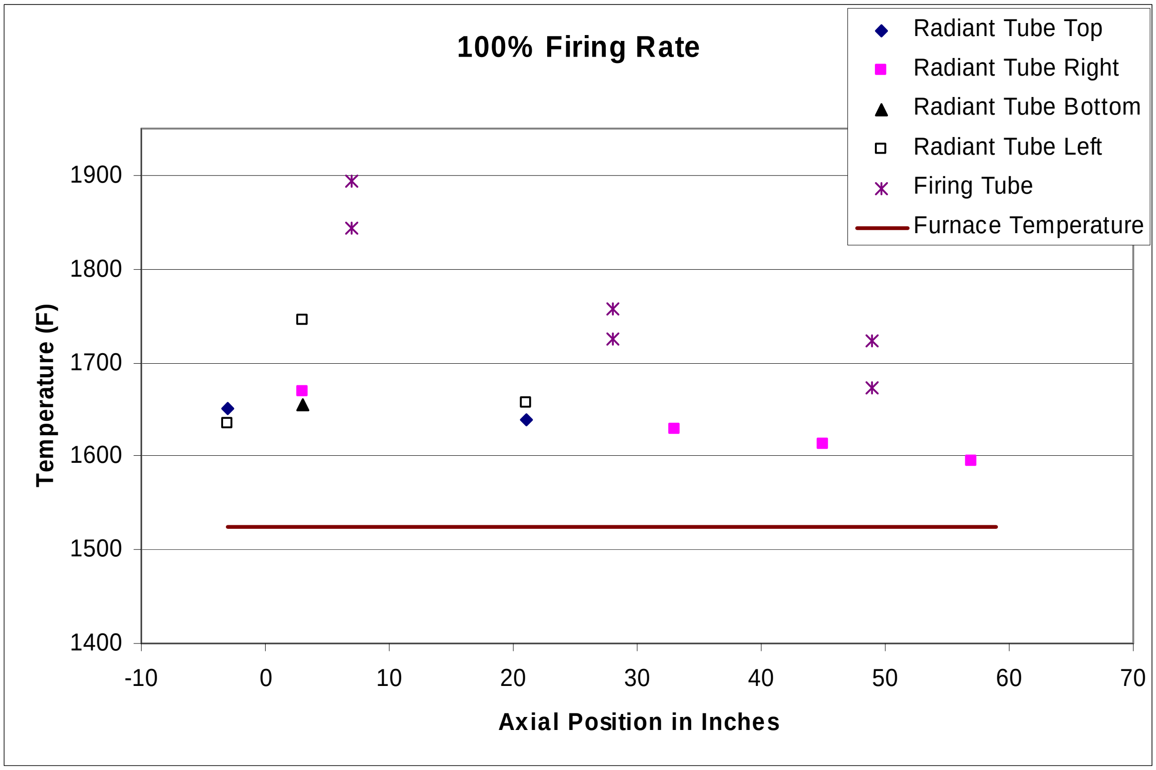


Figure 40. Furnace temperature target 1500 ^{o}F, temperature contours at 100 percent firing rate

Source: Gas Technology Institute, 2008

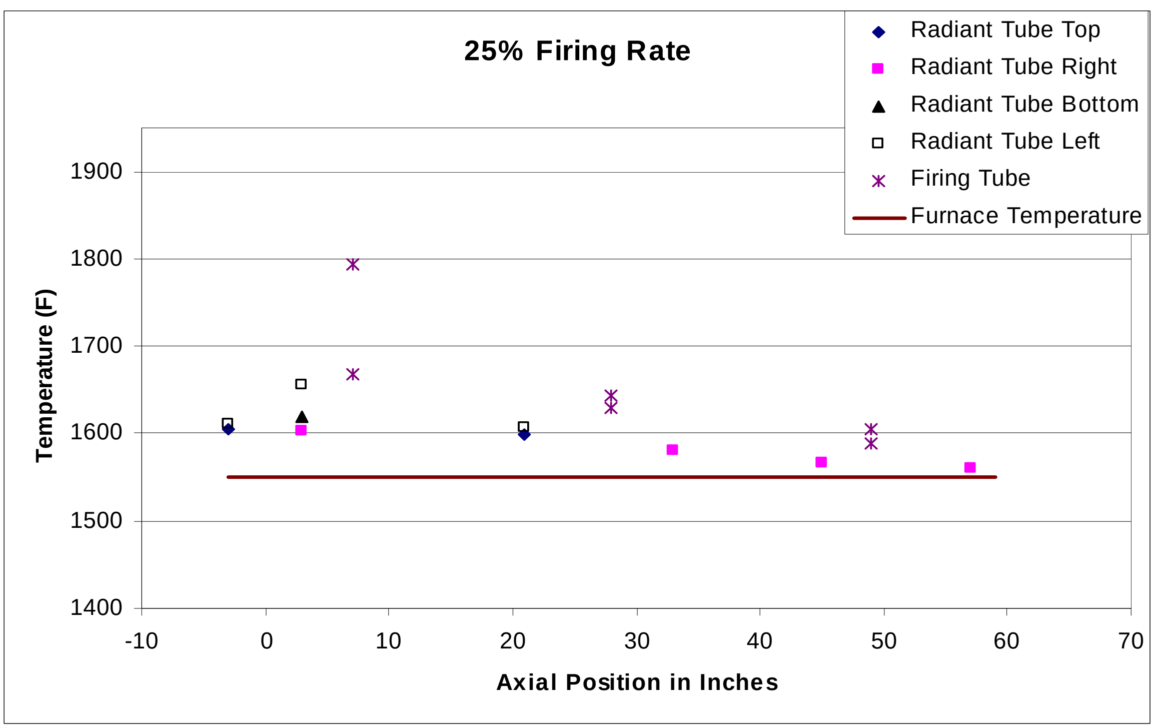


Figure 41. Furnace temperature target 1600 ^{o}F, temperature contours at 25 percent firing rate

Source: Gas Technology Institute, 2008

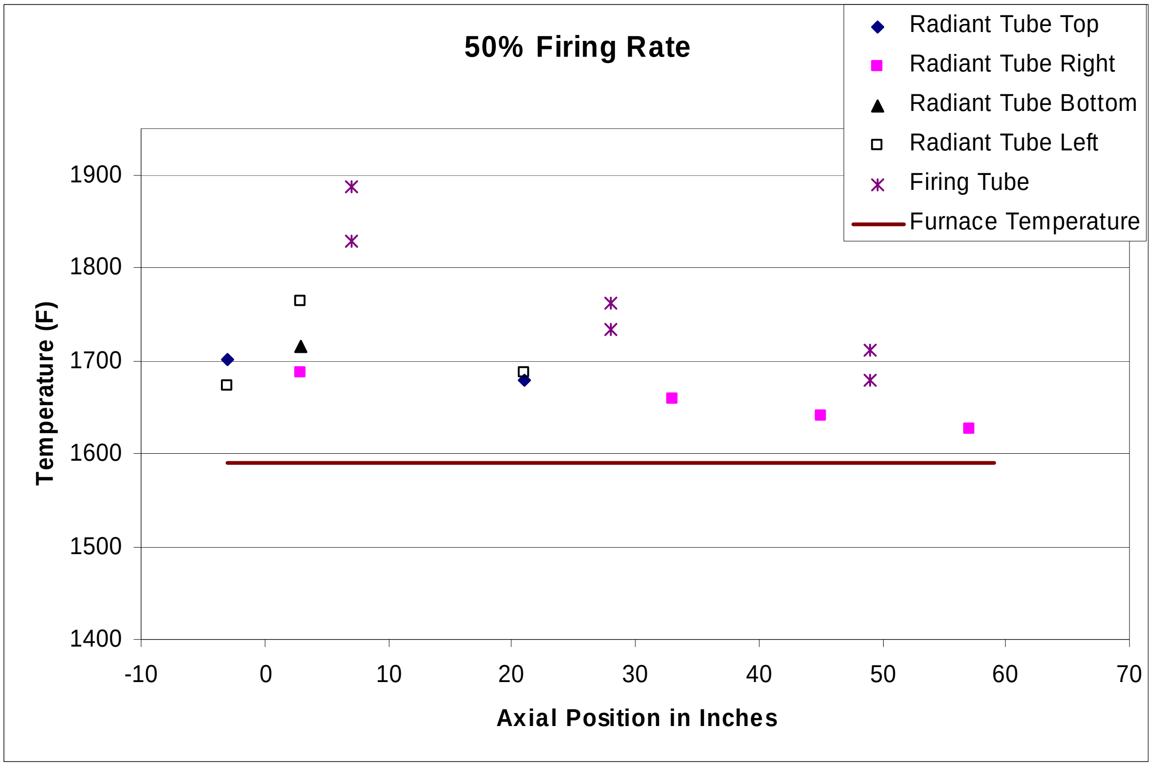


Figure 42. Furnace temperature target 1600 °F, temperature contours at 50 percent firing rate
Source: Gas Technology Institute, 2008

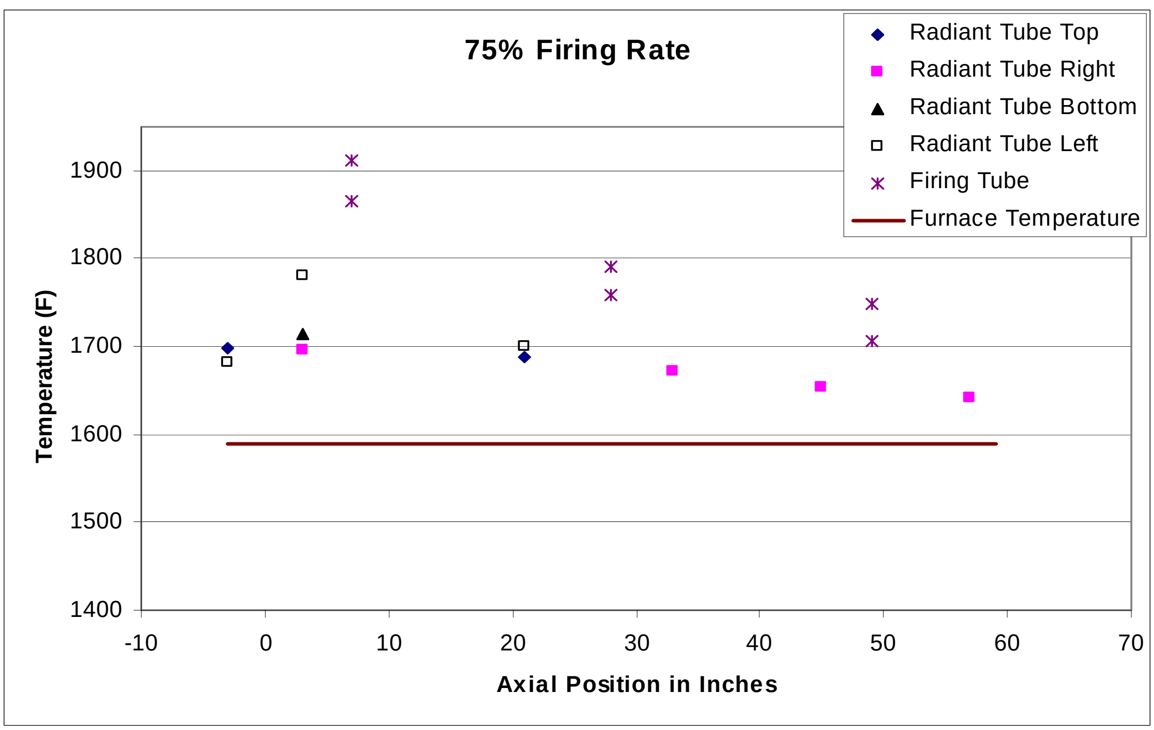


Figure 43. Furnace temperature target 1600 °F, temperature contours at 75 percent firing rate
Source: Gas Technology Institute, 2008

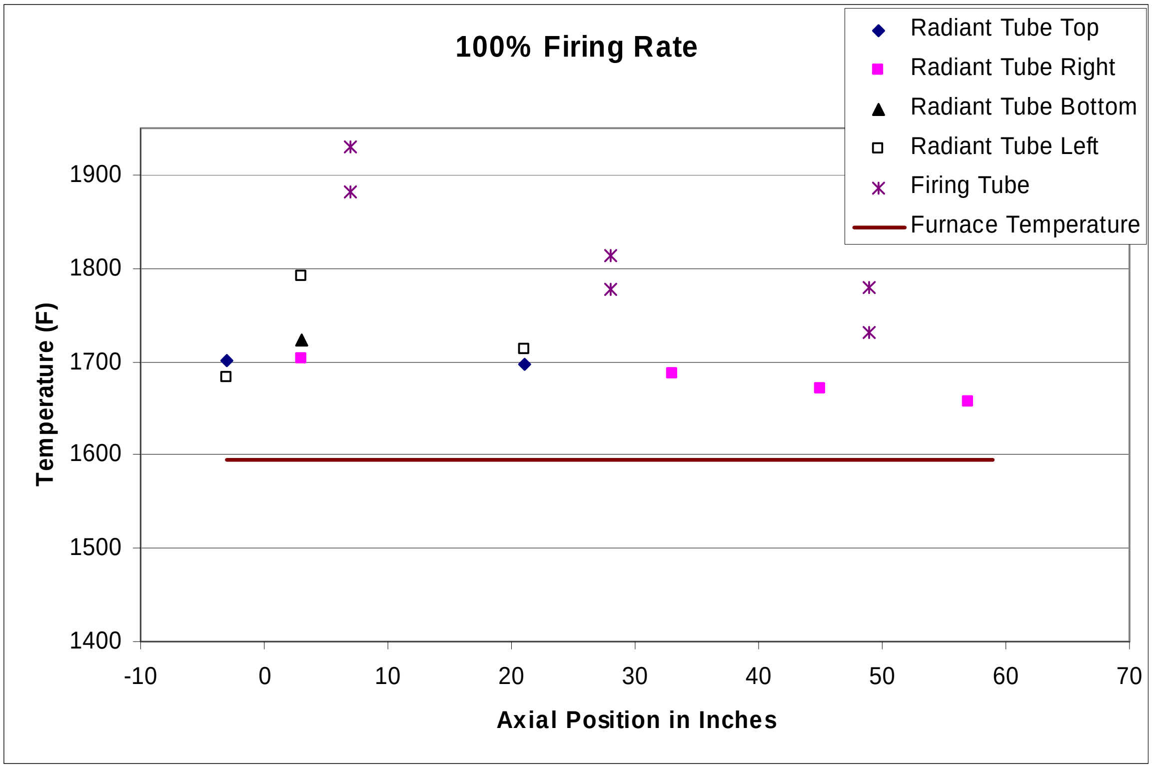


Figure 44. Furnace temperature target 1600 ^{o}F, temperature contours at 100 percent firing rate

Source: Gas Technology Institute, 2008

Photographs

Figure 45. South Side RASERTs in Zone 6, showing aspirated thermocouple installed in the burner body of burner No. 69 South

Source: Gas Technology Institute, 2008

The tubes, water trap (in white water bucket), and hoses connected to the aspirated thermocouple were designed to trap any condensable water before the water reached the ¾ horsepower aspirating pump. The pump created a flowrate of approximately 200 standard cubic feet per hour through the sleeve of the aspirating thermocouple. The velocity of the gas passing over the bead of the thermocouple was estimated to be approximately 197 f/s (based on the volumetric flowrate and the dimensions of the components of the thermocouple); meaning that the true exhaust temperature could be measured with very little error.

3.6. Task 5.0

Pursuant to the successful field trial of the RASERTs at CSI, a subcontractor, Magus Consulting Services, assisted GTI in the development and presentation of two reports, with introductory letters, and mailing of these materials to two groups: Industrial Metal Heat Treating contacts and metal heat treating industrial associations in California. These reports were 2 – 4 pages in length, and briefly described the RASERT technology, potential benefits, results of the field trial, and commercial partner contact information. These reports with accompanying introductory letters were mailed to contacts at Industrial Heat Treating and metal heat treating industrial associations.

4.0 Conclusions and Recommendations

4.1. Conclusions

The RASERTs provided a significant improvement in efficiency, and a reduction in pollutants emitted at high fire, based on a comparison of the performance of the RASERTs and the baseline burners. CSI's engineers have reported that the burners in Zone 6 are usually fired at intermediate to high firing rates, particularly when the type of product being processed calls for a high zone temperature (on the order of 1600 °F). In this range of operation, the RASERTs provide particular advantages. At 100 percent fire with a zone temperature of 1600 °F, the RASERT burner from which detailed data displayed a thermal efficiency of 61.5 percent. During the baseline tests, the cold air burners displayed an efficiency of only 49 percent. Installation of the RASERTs created an improvement in thermal efficiency of 25.2 percent. Emissions of NOx and CO were also reduced dramatically. Under baseline conditions, 117.6 ppmv of NOx and 57.8 ppmv of CO were documented. When the RASERTs were tested, only 70.8 ppmv of NOx and 33.3 ppmv of CO were found. The amount of toxic pollutants emitted also depend on the thermal efficiency; since the RASERTs are more thermally efficient, the overall volume of exhaust gas was reduced, and the total amounts of NOx and CO emitted were reduced proportionately. Thus, under high-fire conditions at 1600 °F, total emissions of NOx were reduced by 51 percent and emissions of CO were reduced by 53 percent.

4.2. Commercialization Potential

The RASERT technology has already undergone extensive field testing, and appears to be a viable commercial product. The manufacturing partner, NAMCO, has developed commercial relationships with a variety of customers, and (once longevity is established in the field) is intending to encourage adoption of the technology in industries where this approach to radiant heating may be used.

4.3. Recommendations

Based on the available data, it appears that the thermal efficiency of RASERTs is highest at lower firing rates. This effect is likely due to convective heat transfer phenomena. The convective heat transfer coefficient of material inside the radiant tube does not vary linearly with firing rate. In any case, it is advisable to fire radiant tube burners at lower firing rates, if possible. For example, in cases where furnace zones have been equipped with more burners than necessary, it is more efficient to fire all available burners are lower rates, rather than to take some burners out of service and fire the remaining burners at higher rates. This will increase the thermal efficiency of the furnace, and reduce emissions of harmful pollutants.

It is also advisable to replace conventional non-recuperated burners with RASERTs wherever possible, in order to increase thermal efficiency and reduce emissions.

4.4. Benefits to California

In the course of this project, twelve non-recuperated, cold air burners in Zone 6 of the No. 1 Galvanizing Line at the Fontana facility of California Steel Industries were replaced with twelve advanced RASERTs. The original burners had no recuperators, and were approximately 50 percent thermally efficient at their rated firing rate. The thermal efficiency of the RASERTs is considerably higher, and reached over 60 percent at the rated firing rate. The RASERTs were shown to be up to 72 percent thermally efficient when fired at a relatively low furnace temperature and at 25 percent of the maximum firing rate for which they were designed.

The actual amount of fuel consumed, and pollution emitted, by burners in Zone 6 depends heavily on the product mix being processed by the facility, and on the utilization of the line. However, during one period of the field test, the line was operated for ten hours under automatic control, at a Zone temperature of approximately 1575 °F. The automatic control system appears to have held the RASERTs at a firing rate of approximately 50 percent during this period, meaning that each RASERT consumed approximately 70,000 Btu/hr of natural gas, and delivered approximately 65 percent of this energy to the furnace in the form of heat. Thus, each RASERT supplied 45,500 Btu/hr of heat to the furnace. The old burners in this zone were only approximately 50 percent thermally efficient, and would have consumed approximately 91,000 Btu/hr of fuel to supply the same 45,500 Btu/hr of heat to the zone. If one assumes that the availability of the line is approximately 90 percent, on an annual basis, and given that the zone conditions observed during the field test are representative of the general operating condition of the zone, it becomes apparent that the RASERT retrofit saved approximately 166 MM Btu per burner annually. For all twelve burners in the Zone, this equates to a savings of 1,990 MM Btu. Given that one cubic foot of natural gas contains approximately 1,000 Btu of energy, this means the retrofit will save approximately 2 million cubic feet of natural gas each year. Assuming that natural gas costs $12/MMBtu, a total of $24,000 worth of natural gas will be saved annually as a result of the retrofit carried out in Zone 6.

The retrofit also reduced harmful emissions of CO and NOx. Exhaust from the old burners contained approximately 120 ppmv of NOx and 60 ppmv of CO. Given that an estimated 2 million cubic feet of natural gas will be saved each year, the retrofit will prevent the emission of 208 pounds of NOx and 97 pounds of CO annually, corresponding to the reduction of natural gas consumption. This represents one manner in which the RASERTs have reduced emissions of pollutants.

However, the new RASERTs also emit lower levels of NOx and CO per cubic foot of natural gas consumed. Since the exhaust from the RASERTs contains approximately 71 ppmv of NOx and 33 ppmv of CO, the new RASERTs will avoid the emission of an additional 284 pounds of NOx and 146 pounds of CO each year.

In total, then, the replacement of 12 cold air non-recuperated burners with the more efficient and inherently lower NOx producing RASERTS has produced direct benefits to California of approximately 2,000,000 cubic feet of natural gas, worth approximately $24,000 annually. The retrofit has also eliminated the emission of approximately 492 lbs of NOx annually and 243 lbs of CO annually. These estimates are predicated on the assumption that the burners are fired at 50 percent of their rated capacity, and the estimated totals scale with firing rate. For example, in applications where the burners would be fired consistently at 100 percent of their rated capacity, the benefits of the retrofit would be approximately twice as large.

More broadly, the retrofit and field trial have demonstrated the commercial viability of the RASERT technology, and increased the likelihood that more of the other radiant tube burner assemblies in use in California will be converted to use RASERTs. As stated above, there are an estimated 5,200 radiant tube assemblies in operation in the state of California. If a sizeable proportion of these can be converted to use RASERTs the impact on air quality and energy consumption in California will be significant.

Based on the experience of GTI Engineering staff, approximately 50 percent of the total radiant tube systems in use in California are likely to be non-recuperated units similar to the burners examined during the baseline test at CSI. Table 5, below, shows estimates of the potential savings of natural gas, energy, NOx, CO, and CO_2 that would result if some or all of these unrecuperated burners were replaced with RASERTs. Each burner is assumed to have the properties of the burners examined at CSI, and to operate under the same conditions found at CSI.

Table 5. Estimates of Natural Gas Savings and Emissions Reductions in the State of California for a range of Unrecuperated Radiant Tube Burners Replaced with RASERT Technology

Source: Gas Technology Institute, 2008

Percent of Unrecuperated Radiant Tube Burners converted to RASERTs:	Estimated Number of Burners Converted:	Natural Gas Savings (cubic feet/yr)	Energy Savings (Btu/yr)	NOx Savings (lbs/yr)	CO Savings (lbs/yr)	CO_2 Savings (tons/yr)
10 percent	260	43,046,640	43	10,645	5,260	2,518
25 percent	650	107,616,600	108	26,612	13,150	6,296
50 percent	1,300	215,233,200	215	53,225	26,299	12,591
75 percent	1,950	322,849,800	323	79,837	39,449	18,887
100 percent	2,600	430,466,400	430	106,450	52,599	25,182

6.0 Glossary

Asp. TC	Aspirating thermocouple
Btu	British thermal unit
CARB	California Air Resources Board
CO	Carbon monoxide
CO_2	Carbon dioxide
CSI	California Steel Industries
DAQ	Data acquisition system
FEA	Finite element analysis
FGR	Flue gas recirculation
GTI	Gas Technology Institute
ID	Internal diameter
NAMCO	North American Manufacturing Co.
NOx	Oxides of nitrogen
O_2	Oxygen
OD	Outer diameter
PPMV	Parts-per-million by volume
SCFH	Standard cubic feet per hour
UTD	Utilization Development Company